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Artificial Daylighting for Color Grading of Agricultural Products*

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IN THE grading of many agricultural products, color is an important quality factor and it is desirable, therefore, that grading be done under favorable conditions of illumination. In a number of industries, as in the cotton trade, it is customary to examine the raw material under light from a north skylight or, lacking that, light from a north window.

Satisfactory natural illumination is so important that this industry goes to great lengths to provide it. What is known as a government-type skylight was developed for cotton classing rooms in the United States Department of Agriculture as long ago as 1914 in connection with services rendered under the Cotton Futures Act and since then under the Cotton Standards Act. Similar skylights have been built into many commercial and government classing rooms since that time. Fig. 1 shows the latest type in the Washington laboratories of the Bureau of Agricultural Economics, a skylight 80 feet long, set facing due north, with glass at an angle of 72° from the horizontal, a circular back to diffuse the light, and no cross beams in the construction to throw shadows. All such rooms are, or should be, painted a neutral gray, so that no one chromatic color will be flattered or discounted more than another.

Satisfactory as such lighting has been, there are many classing rooms that cannot be placed on the top floor, or in a direction such that a long north skylight is feasible. Sometimes when a north window has been used satisfactorily, a new building will go up nearby that cuts off the light, or adds reflections from red or yellow brick walls that are hard to discount properly when classing a sample of cotton. Many rooms are not long enough to use, for skylights less than 40–50 feet long are less satisfactory than those that are longer.

Therefore, to provide a basis for specifications of artificial daylight that will be satisfactory for use when good natural illumination is not available in the grading of farm products in which color is a factor, a systematic and extensive survey has been made of the problem over a period of several years. This report is confined chiefly to work with cotton, although it has been expected that the satisfactory solution of the cotton grading problem would, with only minor adjustments, provide also the answer for other agricultural commodities. Such tests as have been made with other agricultural products do not indicate that there will be a difference, but with no other products have the tests been as critical as with cotton.

As long ago as 1919 artificial daylight lamps were tried out in the Bureau's New York classing room, and approved by the Board of Cotton Examiners. They thought then that the process

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FIG. 1. Washington laboratory of the Division of Cotton Marketing, United States Department of Agriculture. Latest type of skylight developed to provide natural north daylighting for cotton classing rooms.

of classing would be slow under such a lamp, but recommended that one be purchased for use in case of emergency. Later, in 1931, the problem of artificial daylighting for cotton classing rooms was outlined by the writer in a letter to Mr. Norman Macbeth. Even at that time, experience indicated that the light should be well diffused over a large enough area so that the sample could be moved about freely, and that the light should be similar in color to light from a north sky on a slightly overcast day. These specifications are necessary because classifications made under artificial light should agree with classifications made under preferred conditions of natural daylighting.

Information concerning optimum intensities has been lacking, for until the development of instruments for measuring intensities by means of photo-cells, it was a long and tedious process to collect these data. About two years ago, after footcandle meters became readily available, several were purchased and sent to supervisors in charge of more than a dozen government cotton laboratories, most of them with government-type skylights. Instructions were that hourly measurements of the illumination be taken during each working day at several positions along the classing tables, both for a horizontal and a 45° position of the photo-cell. These readings were recorded daily for a period of a month at a time, particularly June and December. Hourly records were kept of sky conditions on a five-step scale: bright, slightly overcast, overcast, rainy or very overcast, very dark. Classing conditions, as called by the classer in charge, were recorded on a five-step scale: very good, good, fair, poor, very poor. Readings were made in government classing rooms in New York, South Carolina, Georgia, Alabama, Louisiana, Tennessee, Mississippi, Texas and the District of Columbia.

From the figures in Table I, compiled from an analysis of these readings, it is evident there is something more than *amount* of light that makes conditions "good" or "poor." Only for overcast December days does there seem to be a definite indication of preference for high illumination. This undoubtedly indicates that the other choices have been merely of illumination intensities

associated with the most favorable energy distributions, which have been previously and quite generally known to be those of a slightly overcast north sky.[1]

Most cotton classing is done in the autumn months, when light is less than maximum, therefore the December figures in Table I are more important than those for June. Data for "good" and "very good" conditions are particularly important. In all but a very few of the cases recorded, conditions of natural lighting were the best available, being obtained through government-type skylights specially built to give optimum conditions.

Individual readings varied widely, as was expected. From 9:00 A.M. to 4:00 P.M. illumination varied by several hundred percent at a single position.

Differences among classing rooms are shown in Table II.

Tables for "very good," "fair" and "poor" classing conditions show variations just as wide.

Average readings for positions in a single office also vary widely.[2] Some offices have poorly lighted classing rooms, even though they get used to poor lighting and call classing conditions "good" on some days.

On the basis of the information received, 60–80 footcandles seems well within the range of what the classer considers good light, although it is obvious that a wide range exists within which conditions may be satisfactory.

On the whole, however, specifications for artificial daylighting are now complete: (1) diffuse illumination over a relatively wide area; (2) color to match slightly overcast north sky; (3) intensity of 50 footcandles a minimum, 60–80 footcandles satisfactory, with little advantage in intensities increased above 100, those above 150–200 to be generally avoided.

The next problem was to find a convenient method of meeting these specifications. After consideration, a choice of lamp-and-filter combination was made. It was expected that there would be difficulty in meeting specifications, therefore the requirements were made as liberal as possible—"at least 30–50 footcandles illumination on the classing tables, a color temperature and relative energy close to I.C.I. Illuminant "C" (tolerance limits 6300°K–7000°K, and for the filters a ratio of transmission at wave-length 610 mμ to that of 700 mμ at least 0.9)." The lamps were to be set behind a diffusing screen, to give the effect of a skylight. The diffusing glass requirements were that "when clear the glass shall transmit at least 91 percent of each wave-length in the visible spectrum" to be delivered sanded or etched on one side.

Provision was made for ventilation, and for a special zinc oxide paint for the interior of the illumination unit, zinc oxide being used in order

TABLE I. *Average of maximum and minimum illumination in footcandles read with a Weston Photo-cell meter for certain sky and classing conditions (for horizontal plane).*

Classing Conditions	Sky Conditions					
	Clear		Slightly Cloudy		Overcast	
	June	Dec.	June	Dec.	June	Dec.
Very Good	108–150	41–50	126–155	52–65	100–150	115–150
Good	118–145	51–60	147–174	64–77	204–252	106–122
Fair	109–149	37–48	138–158	65–75	137–160	80–91
Poor	119–148	31–36	140–168	65–74	99–118	61–70

TABLE II. *Average of maximum and minimum illumination in footcandles for classing conditions called "Good."*

Classing Room	Weather Conditions					
	Clear		Slightly Cloudy		Overcast	
	June	Dec.	June	Dec.	June	Dec.
Washington (new)	180–190	34–45	220–235	45–55	220–250	—
Washington (old bldg.)	120–140	40–50	200–230	65–75	250–275	55–65
Austin	120–150	80–90	130–160	150–160	270–310	175–190
Memphis, S. B.	85–100	55–60	110–120	50–60	—	—
Memphis, G. & S.	140–240	80–105	220–295	70–100	200–250	—
Houston	130–140	50–60	140–150	75–85	150–160	—
Charleston	130–150	45–55	110–115	50–60	250–350	140–150
Atlanta	60–70	75	130–140	60–75	—	90
Savannah	130–150	—	140–150	60–70	—	—
New Orleans	70–90	12–13	80–110	14–19	90–125	—
Dallas	180–220	30–40	150–185	55–70	—	—
Stoneville	70–100	54–60	140–200	75–90	200–300	120–125
Average	118–145	51–61	147–174	64–77	204–252	116–122

[1] Light from a clear blue sky is very generally called "glaring," yet, as can be seen from Tables I and II, the illumination intensity for such days is well below that of slightly cloudy, or even of overcast days. It has seemed obvious that high color temperature should be avoided.

[2] Anyone having use for detailed data for horizontal and 45° positions can obtain photostatic copies of summary tables by writing to the Bureau of Agricultural Economics, United States Department of Agriculture, Washington, D. C.

FIG. 2. Artificial daylight installation in Washington laboratories, Division of Cotton Marketing, United States Department of Agriculture. This type of installation was developed for use in the color grading of agricultural products.

to keep the energy reflected in the infra-red as low as possible.[3]

The space available for experimental purposes was 6×11 feet. The first installation, which in appearance is similar to the one shown in Figs. 2 and 3, used fifteen 1000-watt lamps, with Corning Daylite filters (Macbeth 2ACL9) 5.5 mm thick. The lamps were set approximately 24 inches between centers, three rows of five lamps each, the filters being 20 inches above the diffusing glass set eight feet from the floor. The result gave an average intensity of about 100 footcandles. With 500-watt lamps, the intensity was about 50 footcandles. Figures for footcandle distribution taken with a Weston cell instrument, corrected for daylight, are shown in Table III. Such intensities were far beyond what we had hoped to get, and provided a wide tolerance within which to work. The walls were painted a neutral gray, about Munsell N 7/.

When cotton samples were placed on the table and examined under this light, they looked too creamy. The color of the illumination was well up to that of Illuminant "C" adopted by the International Commission on Illumination[4] for average daylight. But the fact that an internationally adopted standard had been used in the hope that cotton men, unaware of the substitution, would accept "average daylight" as a good substitute for slightly overcast north sky, meant nothing.[5] The cotton men did call the

[3] Dr. A. H. Pfund suggested zinc oxide for this purpose, mixed with cold water or as little binder as possible, Dr. G. F. A. Stutz, contributed the material, and Mr. E. F. Hickson, National Bureau of Standards, mixed it in one of his mills.

[4] I. G. Priest, "Report of the Work of the Colorimetry Committee of the International Commission on Illumination and the Actions Taken at the Meeting in Cambridge, England, September 1931," J. Opt. Soc. Am. **22**, 431 (1932). Deane B. Judd, "The I.C.I. Standard Observer and Coordinate System for Colorimetry," J. Opt. Soc. Am. **23**, 365 (1933). In connection with the adoption of 6500°K as representative of average daylight, reference should be made to the discussion of "White Light" prepared and circulated by Priest within this country in July 1931 as a part of the preparation for action on that subject by the I.C.I. Colorimetry Committee which met and adopted standards the following September. I.C.I. File Reference Document "15 U.S. 6" (National Bureau of Standards file).

[5] Perhaps this may only indicate that there is more difference in color temperature than has been supposed between overcast sky from the south (found by Gibson to be closely 6500°K) and overcast sky from the north. It

FIG. 3. Looking into the lamp-and-filter arrangement, above the diffusing glass "skylight" shown in Fig. 2.

illumination "satisfactory." They thought that work could undoubtedly be done under it after a classer accustomed himself to it. But they did not think it a good substitute for the slightly overcast north sky they prefer and are accustomed to use. This point is important, for there is a psychological as well as a physical standard to be maintained. If there is doubt—if the light is only "satisfactory" instead of really "good"—then artificial daylighting will be used only when conditions make it absolutely necessary. If artificial daylighting is right, it will, in cases of conflict, gradually be preferred to natural daylighting because of its relative constancy.

TABLE III. *Footcandle distribution 32" from floor, color temperature of lamp-and-filter combination about that of "C" illuminant. Upper figures for 1000-watt lamps; lower figures for 500-watt lamps.*

WALL SIDE

WALL SIDE						WALL SIDE
	77 37.5	93 46.5	102 49.5	98 47.5	85 40	
	85 41.5	105 49.5	118 58	109 51	88 43	
	72 35	90 43	98 47	90 43	73 35	

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There is no more critical cotton classing group than the committee in charge of making up the Universal Cotton Standards. They must match the color of cotton far more accurately than other cotton classers would generally consider necessary. Therefore, if conditions imposed in making the standards on which the entire cotton trade base their grades are met, conditions imposed by any other less critical group will also be met.

Furthermore, it should be pointed out that the "too-yellow" effect on the cotton under lamp-and-filter at about "C" illuminant was evident to any color trained person, not necessarily to a cotton classer only.

One big advantage in selecting a lamp-and-filter combination was that both the lamps and filters could be changed or adjusted until a satisfactory standard could be reached.

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seemed to the writer, in suggesting I.C.I. "C" Illuminant for a first trial—it having been adopted as a standard for average daylight—that it would probably be close to the color of an overcast sky.

So the filter was changed, still using Corning Daylite, but this time (Macbeth BDK11) 5.5 mm thick that produced, when used with lamps operated at 3000°K,[6] a color temperature of about 7400°K. After cotton standards were examined under this new light, it was accepted by the Cotton Appeal Board as providing light sufficiently like that from the overcast north sky which they prefer to make the cotton look natural to them. The present installation uses 1000-watt lamps around the outer rows, with 500-watt lamps in the center. The light distribution under the lamps is shown in Table IV.

Ventilation is extremely important in such an installation as this one. The air must be kept moving behind the diffusing glass so that heat is not allowed to accumulate. With proper control, the diffusing glass panels should not become hot even after several hours operation of the lamps.

At the present time the matter of developing heat-absorbing glasses to produce a color temperature in the 7000°–8000° range is being investigated by Dr. H. P. Gage. Without the use of heat-absorbing glass there is, of course, a certain effect from radiant heat, for ventilation cannot solve that difficulty. A white paint, which absorbs instead of reflects the infra-red rays, applied to the interior of the illumination unit should be some help. We have no measurements of the reflectance of our white paint for the infra-red, but hope that it is fairly low. Our installation is in a corner, where the air is more or less pocketed. Measurements made on a single day showed that while air temperatures under the 1000-watt lamps went up 9°F after 3½ hours of continuous operation, the daily temperature rose 7°F. On another day while the air temperature under 500-watt lamps went up about 6° after four hours of continuous operation, the daily temperature rose 5°. Air temperatures do not, however, tell the story of radiant heat as felt through the skin when one stands under the unit. Tall, bald-headed men notice it, but many others do not.

Since the above installation has been made, a box unit has been developed for installation in one of our field offices. It should be remembered that unless equivalent filters are specified, even though the unit comes from the same maker, the light will not necessarily be the same as that reported in this paper.

At the time when the Bureau's laboratories began work on this subject, no satisfactory method of practical artificial daylight illumination was available in any cotton classing offices of which its technologists had knowledge. Coordinately, however, a special carbon-arc unit has been developed and installed in the classing rooms of a large cotton firm in Houston, Texas. The same principle of a large source of diffuse illumination was followed, by placing the arc in an illuminating box with a diffusing glass bottom.

Because so many inquiries have been received concerning artificial daylighting for cotton classification as a result of the Bureau's work and that of the carbon arc development, and because of the Bureau's interest not merely in a single type of installation, but in all possibilities for providing a satisfactory answer, a study of color temperature[7, 8] and energy distributions has been

[6] Dr. W. E. Forsythe supplied figures for color temperature of 500-, 750- and 1000-watt lamps of type PS52 used. (Letters of December 20, 1937 and March 31, 1938.)

1000-WATT, 110-VOLT		750-WATT, 115-VOLT		500-WATT, 115-VOLT	
OPERATING VOLTAGE	°K	OPERATING VOLTAGE	°K	OPERATING VOLTAGE	°K
119.6	3097	120	3010	120	3020
114.8	3048	115	2955	115	2977
110	3000	110	2910	110	2931
105.2	2953				

These lamps are rated at 1000-hour life. Regarding color temperature change in tungsten lamps see: Deane B. Judd, "Changes in Color Temperature of Tungsten Filament Lamps at Constant Voltage," J. Opt. Soc. Am. **26**, 409 (1936).

TABLE IV. *Footcandle distribution 32" from floor, lamp-and-filter combination about 7400°K. Five lamps in center group are 500 watt, others 1000 watt.*

WALL SIDE

WALL SIDE					WALL SIDE
	49	58	61	60	50
	49	60	64	63	53
	46	55	62	56	50

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[7] Deane B. Judd, "Estimation of Chromaticity Differences and Nearest Color Temperature on the Standard 1931 I.C.I. Colorimetric Coordinate System," J. Opt. Soc. Am. **26**, 421 (1936). H. P. Gage and Norman Macbeth, "Filters for Artificial Daylighting, Their Grading and Use," Trans. I.E.S. **31**, 995 (1936).

[8] See also, Irwin G. Priest, "Proposed Scale for Use in Specifying the Chromaticity of Incandescent Illuminants and Various Phases of Daylight," J. Opt. Soc. Am. **23**, 41 (1933). The proposal made in this paper should receive

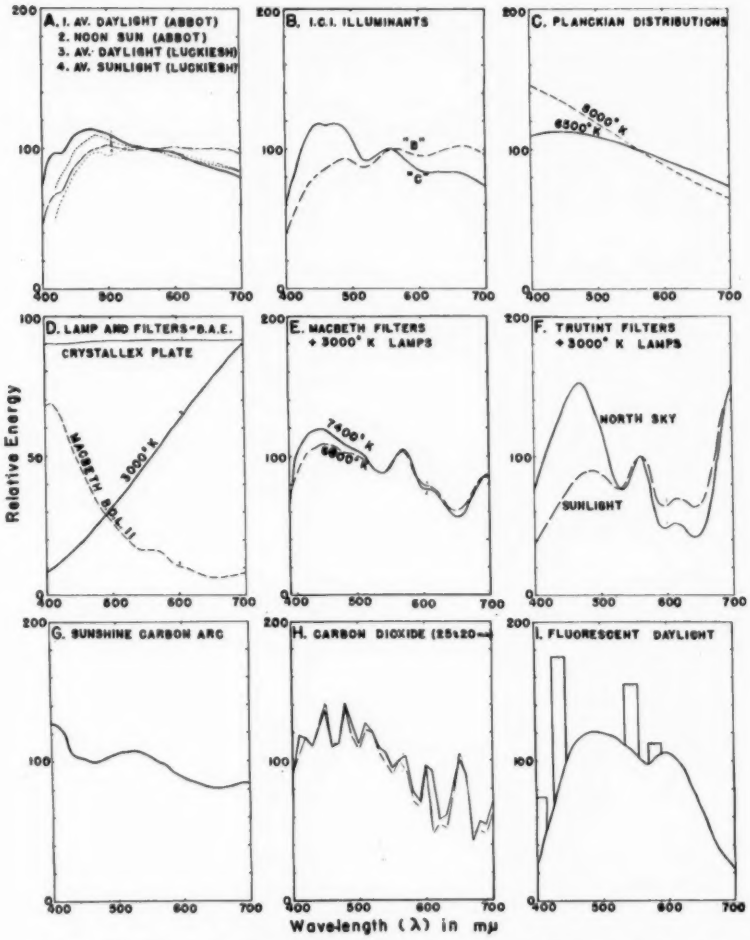

FIG. 4. Relative energy curves, reduced to 100 at 560 mμ, of several standards referred to in work with daylight, and several sources (with and without filters) that have been suggested or tried out for use as artificial daylight. Only in *D* is the scale of relative energy different, changed to give actual transmission values for the two filters.

made of several sources of illumination that are being made available for use as artificial daylight. These data have been put into relative energy curves that may be easily compared, each reduced to 100 at 560 mμ (Fig. 4), and into a large scale (*x*, *y*)—plot (Fig. 5).

First, energy distributions generally used as standards should be shown. Those for Abbot's sun outside the earth's atmosphere,[9] for Abbot's mean noon sun (Washington),[9] and average daylight and sunlight as given by Luckiesh and Taylor[10] for Cleveland, are shown in Fig. 4(A).

serious consideration. It would be much easier to work in Priest units of microreciprocal degrees of color temperature than in color temperature itself. For reference these units are indicated in Fig. 5 as "mireds."

[9] A. C. Hardy, *Handbook of Colorimetry*, 1936. The Abbot data in this book (Tables VI and VII) were prepared by Dr. K. S. Gibson and supersede previously published data.

[10] The most recent paper by Luckiesh, Taylor and Kerr which gives these energy curves, gives curves also for Mercury and tungsten lamp combinations, and for Ivanhoe Trutint noon sunlight and north sky light: "Artificial White Light," General Electric Review, February 1938. See also A. H. Taylor, "The Color of Daylight," Trans.

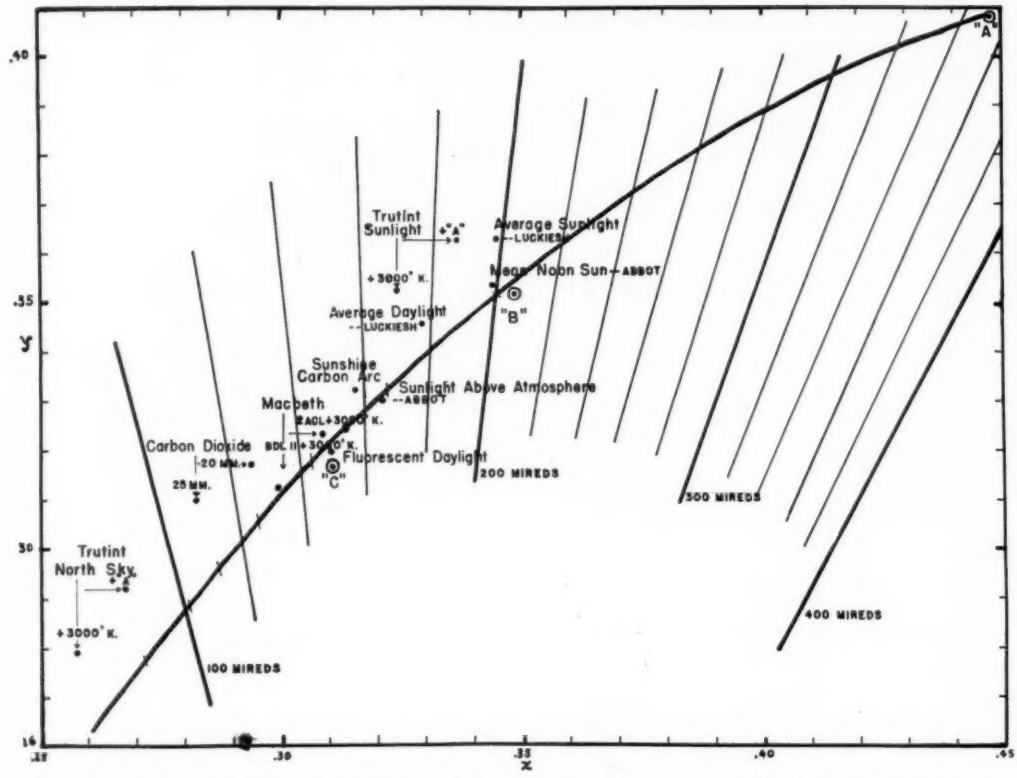

FIG. 5. A portion of the I.C.I. (x, y) diagram showing the Planckian locus extending from "A" Illuminant (at 2848°K) to a color temperature considerably higher than 12000°K. Iso-temperature lines are given in microreciprocal degrees (mireds). Illumination standards generally referred to for daylight are shown and several illuminants that have been proposed for use as artificial daylight.

Standards "B" and "C" adopted by the International Commission on Illumination, "B" generally thought of as representing noon sunlight, "C" representing average daylight, are shown in 4(B).[4] Planckian distributions for 6500°K and 8000°K are shown in 4(C).[11]

Energy curves of the diffusing glass, filter and lamps used in the final Bureau of Agricultural Economics unit are shown in 4(D). The two Macbeth units, used with lamps at 3000°K, are shown for comparison in 4(E): the combination approximating "C" (marked 6800°K) was the one tried and rejected because it was not high enough in color temperature; the 7400°K combination is the one now installed in the Bureau of Agricultural Economics color laboratory.

Then other filter combinations should be mentioned. There is an Ivanhoe Trutint filter supplied in Sunlight and North Sky lamps.[10] Energy curves for commercial samples of these filters, plus a lamp at 3000°K, are shown in Fig. 4(F).[12]

The high intensity carbon arc developed in connection with displaying colored motion pictures, is a fairly new "daylight" source. As mentioned, a similar type of arc is being tried out directly in a unit for cotton classification. It has

I. E. S. 25, 154 (1930), and "Spectral Distribution of Energy in Common Illuminants," General Electric Review, Sept. 1934.

[11] Davis-Gibson, "Filters for the Reproduction of Sunlight and Daylight and the Determination of Color Temperature," Misc. Publication, National Bureau of Standards, No. 114, 1931.

[12] Unless otherwise noted, transmission curves for filters given in this paper were measured on a General Electric Recording Spectrophotometer, some in the laboratories of the Interchemical Corporation, some at the National Bureau of Standards.

the advantage of being a very efficient source in comparison with a source-and-filter combination. The color temperature is near to 6500°K. A curve of relative energy distribution of high intensity Sunshine carbon taken from data supplied by the maker is shown in Fig. 4(G).[13]

Carbon dioxide lamps are still another "daylight" source.[14] The color temperature is naturally high, the 25-mm tube somewhat higher, and the 20-mm tube just lower than that to which the Bureau of Agricultural Economics lamp-and-filter combination was finally changed. Relative energy curves calculated from E.T.L. curves made for the manufacturers, and supplied by them, are shown in Fig. 4(H).

The new fluorescent lamps have a tube known as Daylight Fluorescent. Its properties are described in a recent paper by Inman.[15] A relative energy curve is shown in Fig. 4(I).

The colors of these several standards and illuminants are shown on an I.C.I. (x, y) diagram relative to the Planckian locus in Fig. 5.

[13] Similar to curves shown in bulletins describing Sunshine Carbon. See also a recent paper by Bowditch and Downes, "Spectral Distributions and Color-Temperatures of the Radiant Energy from Carbon Arcs Used in the Motion Picture Industry," J. Soc. Mot. Pic. Eng. **30**, No. 4 (1938).

[14] Thomas J. Killian, "Artificial Daylight from Carbon Dioxide Lamps," J. Opt. Soc. Am. **28**, 49(A) (1938). Points emphasized are that with tubes having the same characteristics, the quality and quantity of light remain constant.

[15] G. E. Inman, "Characteristics of Fluorescent Lamps," Trans. I. E. S. paper presented before the thirty-second annual convention of the Illuminating Engineering Society, August 29–31, 1938.

In Conclusion

The color measurements laboratory of the Bureau of Agricultural Economics believes that a standard should be established for artificial daylight that will provide a reference point for use in meeting the needs of grading and inspection work in fields in which color is an important grade or quality factor. Such a standard might eventually provide a "D" Illuminant to be added to the "A," "B" and "C" already adopted internationally as reference points for color work, "B" and "C" already representing two phases of daylight.

The information in this paper is presented with such a goal in mind. What is presented here has been done chiefly in connection with cotton classification. The lamp-and-filter combination resulting in the energy distribution shown, with I.C.I. trilinear coordinates roughly approximating $x=0.30$, $y=0.31$, gives satisfactory illumination, but there is opportunity for development. Tungsten lamp-and-filter combinations require heat removal. And perhaps other illuminants, such as the carbon arc or the carbon dioxide tube, can be developed and adapted to meet the specifications found necessary:

(1) Diffuse illumination nearly uniform over a wide working area.
(2) Color to match slightly overcast north sky.
(3) Intensity of 60–80 footcandles at horizontal working plane, with little advantage in intensities increased above 100 footcandles.

The Colors of Mosaic Powder Films*

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(Received October 20, 1938)

THE curious phenomena under discussion are observed when white pigment particles (TiO_2, ZnS, etc.) are deposited on glass in a layer one particle deep. As the result of a special procedure, the particles are caused to collect in discrete areas separated by pigment-free areas—thus forming a mosaic. If a distant incandescent lamp be viewed through a mosaic film containing particles of the proper size, brilliant colors are observed. In the following it is proposed to discuss the origin of these colors.†

If a mosaic film of commercial TiO_2 pigment be viewed in transmitted light, little if any color will be revealed. If then a film of linseed oil ($\mu=1.48$) be allowed to flow over the pigment without disturbing the mosaic pattern, brilliant colors are observed. A photomicrograph (linear magnification 1200×) of such a mosaic film is shown in Fig. 1(a). If, now, a second glass plate be laid on the wet film, and if this plate be moved gently back and forth so as to disperse the pigment particles in the oil, all trace of color will vanish. A photomicrograph (magnification 1200×) of the dispersed pigment is shown in Fig. 1(b). The fact is then established that the existence of a mosaic pattern is essential to the appearance of saturated colors.

The preparation of mosaic films is carried out in the following manner: half a teaspoonful of a commercial white pigment (zinc sulfide, titanium oxide, white lead, etc.) is placed on a ground glass plate; enough amyl alcohol is poured over the pigment to yield a moderately stiff paste, which is mulled for about two minutes with a glass muller. Next some camphor-free nitrocellulose, dissolved in amyl acetate, is added to the pigment paste and the mulling is continued until the mixture is uniform. A drop of this mixture and a drop of clear amyl alcohol are placed on the upper surface of a microscope slide. A uniform mixture is produced by means of a second microscope slide which crosses the lower slide perpendicularly and which is moved back and forth, parallel to the long side of the lower slide. As soon as the mixture between the plates has become translucent, the upper plate is slid entirely off the lower one—thus leaving a thin, wet film on the lower slide. The thickness of the fluid layer is so slight that floating pigment particles attach themselves alongside of, rather than on top of, anchored ones. By blowing gently the volatiles are quickly evaporated, leaving behind a mosaic film with a nitrocellulose binder. The slide is next placed on an electric stove so as to burn off the nitrocellulose without disturbing the mosaic pattern.

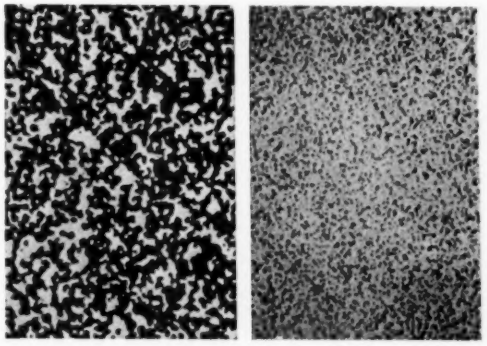
This mode of procedure is not satisfactory for the reason that the mosaic films are not highly reproducible. It is essential that such variables as the consistency and concentration of the paste, the thickness of the film and the planarity of the glass plates all be correct simultaneously. Accordingly the procedure was modified by using the well-known technique employed in forming thin films by allowing a drop of a dilute nitrocellulose amyl-acetate solution to spread out on the surface of water. A drop of the rather fluid pigment-nitrocellulose mixture was allowed to spread out on the surface of water contained in a circular dish about ten inches in diameter. Upon evaporation of the volatiles, a whitish film remained, and this could be lifted off in part by introducing a microscope slide beyond the edge of the film. Upon burning off the nitrocellulose, a film resulted which, under the microscope, revealed a mosaic structure made up of "clear centered" pigment particles. It is only when the pigment layer is one particle deep that a minute spot of light will be seen at the center of each particle. This procedure has been successful only in the case of TiO_2 and then only if the water on which the film was spread contained a small amount of HCl. When the proper mode of procedure shall have been worked out for other pigments also, it seems hopeful that, since all materials and operations are amenable to standardization, reproducible films may be realized.

* Read before the Optical Society of America at its meeting at Niagara Falls, Ontario, October 27–29, 1938.

† The term "color" is used in a broad sense which extends its applicability into the infra-red, also.

Data for spectral transmission curves were obtained by means of a glass (Fuess) monochromator which covered the range: 0.4μ to 2.7μ. The radiations from a 32-cp automobile headlight lamp were focused on the slit of the monochromator, and intensities were measured by means of a single-junction vacuum thermopile connected to a Leeds & Northrup H-S galvanometer. Since preliminary experiments had shown that the pigment film scattered considerable white light, it was found desirable to minimize this effect by mounting the film, not immediately in front of the slit, but near the condensing lens.

When the transmission curves for the materials discussed in connection with Fig. 1 were plotted, it was found (Fig. 2, curve *B*) that, whereas the curve for the oil-dispersed pigment followed the normal (Rayleigh) form,[1] the oil-covered mosaic film revealed a pronounced minimum near $\lambda=0.58\mu$ (Fig. 2, curve *A*). Because of this



(a) (b)

FIG. 1. Photomicrographs of TiO_2 (linear magnification 1200×): (a) mosaic film showing brilliant colors, (b) particles dispersed—no colors.

minimum in the yellow, the film appeared reddish blue in transmitted light.

Upon measuring the spectral transmission of mosaic films prepared, respectively, from fine, medium and coarse pigments, it was found that the transmission minimum was shifted to greater wave-lengths as the particle size increased (Fig. 3). Here curve *A* applies to a fine ZnS pigment of particle size[2] 0.39μ; *B*, to commercial ZnS, particle size 0.51μ, and *C* to sublimed white lead (S.W.L.), particle size 0.67μ. It was further found that, if one of these films be covered with a microscope slide and if a liquid of higher refractive index (amyl alcohol, linseed oil, etc.) be allowed to crawl between the plates, thus surrounding the pigment without disturbing the mosaic structure, the transmission minimum was shifted to shorter wave-lengths. A typical curve of this type is shown in Fig. 4. The pigment is S.W.L. and the media are air (curve *A*) and amyl alcohol ($\mu=1.408$, curve *B*).

In spite of the fact that minima often lie in the infra-red where refractive indices of pigment and liquid are not known, it seemed worth while to try to explain the presence of the transmission minima on the basis of "Young's theory of the colors of mixed plates."[3] The mosaic would, accordingly, be interpreted as consisting of regions of contiguous pigment particles of equivalent thickness t (Fig. 5) and refractive index μ_2 separated by pigment-free regions of refractive index μ_1. Following the well-known argument: if the retardation of the ray 2 over the ray 1 is Δ, then when

$$\Delta=(\mu_2-\mu_1)t=n\lambda/2, \quad n=1, 3, 5 \text{ etc.}, \quad \cdots, \quad (1)$$

destructive interference will ensue and as a result, interference minima[4] will exist at wave-lengths λ, $\lambda/3$, $\lambda/5$, etc. Interpreting then the pronounced transmission minima previously found as "interference minima" of order $n=1$, it was concluded that, on the basis of expression (1), the value of

$$t=\lambda/2(\mu_2-\mu_1) \quad (2)$$

for air and for oil immersion, respectively, ought to remain constant. Accordingly, the wave-lengths of the transmission minima for five different pigments were determined for both air and oil as the surrounding media (μ_1). For each pigment the two values for t came out essentially

[1] A. H. Pfund, J. Opt. Soc. Am. **24**, 143 (1934).

[2] I am indebted to Dr. C. E. Barnett of the New Jersey Zinc Company for having measured these particle-diameters by the microscope method.

[3] R. W. Wood, *Physical Optics*, Third edition, p. 279.

[4] The terms "interference minima" are used to replace the cumbersome phraseology: "minima of transmission caused by a maximum of destructive interference." If further justification is required, see R. W. Wood, *Physical Optics*, Third edition, pp. 170, 172.

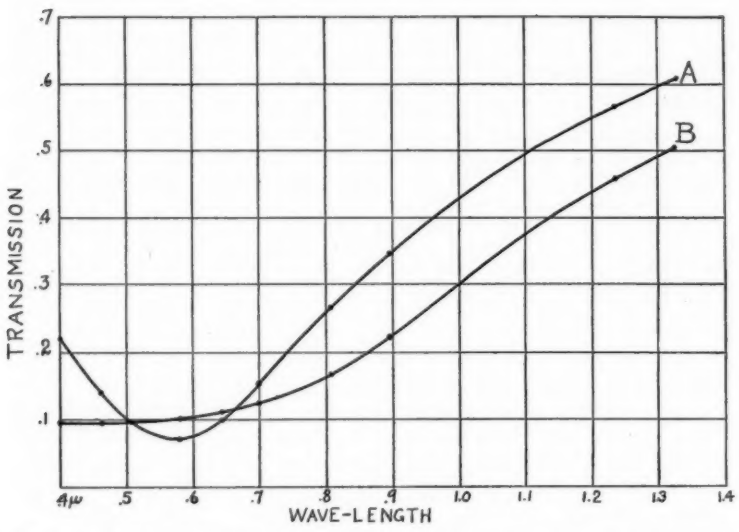


FIG. 2. Spectral transmission curves for films shown in Fig. 1: *A*—mosaic film, covered with linseed oil, *B*—pigment particles dispersed in linseed oil.

the same. The numerical values for t (air immersion) are presented in Table I where the corresponding values of the particle diameter D,[5] are also recorded. While the agreement between t and D is but moderately good for S.W.L., the value of t for fine ZnS is but half that of D. The reason for these discrepancies is not obvious. All that can be claimed for these determinations is that they place the pigments in the proper order as to particle size.

If there be any virtue in the interference theory, then it ought to be possible to evaluate, approximately, the refractive index of the pigment. Accordingly, mosaic films of the several pigments were prepared and covered with a clear microscope slide. Transmission curves were obtained under the two conditions: (1) pigment surrounded by air; (2) pigment surrounded by oil, amyl alcohol or some fluid of higher refractive index. A characteristic pair of such curves for S.W.L. is shown in Fig. 4. Considering the two expressions for t (Eqs. (1) and (2)) for air and liquid immersion, respectively, it is easily possible to show that

$$\mu_2 = \frac{\mu_1\lambda_0 - \mu_0\lambda_1}{\lambda_0 - \lambda_1}$$

where μ_2 = refractive index of pigment, $\mu_0 = 1$ = refractive index of air, μ_1 = refractive index of liquid, λ_0 = wave-length of transmission minimum (air immersion), and λ_1 = wave-length of transmission minimum (liquid immersion).

Since the wave-lengths of the minima cannot be determined precisely, and since the refractive index of the liquid at λ_1 is not always known, measurements of μ_2 cannot as yet be made to an

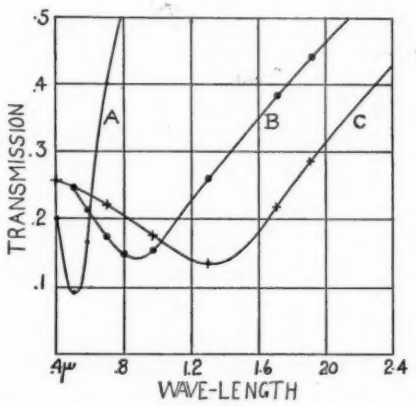


FIG. 3. Spectral transmission curves showing shift of minimum toward longer wave-lengths with increase in particle-size: *A*—fine ZnS, particle diameter 0.39μ, *B*—finished ZnS, particle diameter 0.51, *C*—S.W.L., particle diameter 0.67.

[5] Microscope measurements due to Dr. C. E. Barnett.

accuracy higher than ± 0.1. The results obtained are shown in Table II where the accepted value of μ_2 for a given substance applies to massive crystals. The agreement is quite fair. Perhaps better results will be obtained when the transmission minima are deepened and narrowed as a result of working with pigments of uniform particle size.

The final experiment is based on the following considerations: if we look upon the pigment particles in a mosaic as the equivalent of a thin plate, then it follows that if the angle of incidence i on this plate be increased, the retardation of ray 2 over ray 1 (Fig. 5) will increase, as a result of which the minimum will be shifted to greater

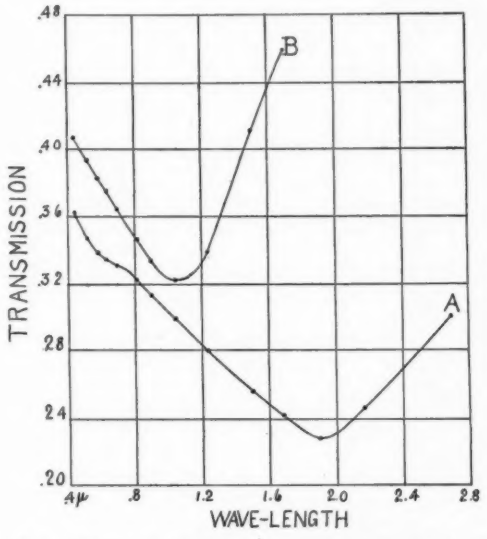


FIG. 4. Showing the shift of the transmission minimum toward shorter wave-lengths as the refractive index of the medium covering the film is increased: *A*—mosaic film of S.W.L., medium, air, *B*—mosaic film of S.W.L., medium amyl alcohol, $n=1.408$.

wave-lengths. From relation (1) it follows that for

$$i_1=0,\ \Delta=(\mu-1)t=n\cdot\lambda_1/2, \tag{3}$$

$$i_2>0,\ \Delta=t/(\cos r_2)(\mu-\cos(i_2-r_2))=n\lambda_2/2, \tag{4}$$

where r_2 is the angle of refraction within the plate corresponding to i_2. To test these predictions, the transmission curves of a dry mosaic film of TiO_2 were obtained for $i_1=0$ and $i_2=48°$, respectively. These curves, which are presented in

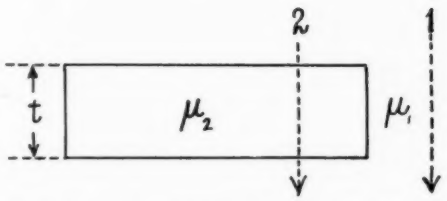


FIG. 5. Schematic replacement of a pigment "island" by a uniform plate of thickness t and refractive index μ_2.

Fig. 6, show that the minimum is shifted from 0.81μ (curve *A*) to 0.92μ (curve *B*). Eliminating t from the above expressions (3) and (4) and inserting the values $\mu=2.53$ (TiO_2) and $\lambda_1=0.81$, the value of λ_2 was calculated to be 0.93μ—in close agreement with the observed value 0.92μ. Finally, the transmission of a film of ZnS, thoroughly dispersed in linseed oil, was similarly determined at the angles of incidence 0° and 48°, respectively. This pigment-vehicle mixture showed a flat transmission minimum near 0.58μ. As is evident from curves *C* and *D* (Fig. 6), this minimum remained fixed.

Since the phenomena under investigation are of the "borderland" type (particle-size of the order of magnitude as the wave-length), it seemed of interest to attempt an explanation on the basis of scattering. The theories of scattering were developed notably by Debye[6] and Mie.[7] Later Stratton and Houghton,[8] basing their work on that of Debye and Mie, calculated the scattering of spherical water droplets (large or small with respect to wave-length). Their curve[9] is presented in Fig. 7, where the abscissae are $2\pi\lambda/r$ (λ=wave-length, r=particle radius) and where the ordinates K are a function of the attenuation coefficient γ, according to the relation $\gamma=\pi r^2 n' K$, where n'=the number of droplets per cm^{-3}. For the sake of ease of discussion

TABLE I.

PIGMENT	μ OF PIGMENT	λ_{MIN}	t	D
Fine ZnS	2.37	0.52μ	0.19	0.39
Finished ZnS	2.37	0.90	0.33	0.51
S.W.L.	1.93	1.33	0.72	0.67

[6] P. Debye, Ann. d. Physik **30**, 57 (1909).
[7] G. Mie, Ann. d. Physik **25**, 377 (1908).
[8] J. A. Stratton and H. G. Houghton, Phys. Rev. **38**, 159 (1931).
[9] E. O. Hulburt, J. Opt. Soc. Am. **25**, 125 (1935).

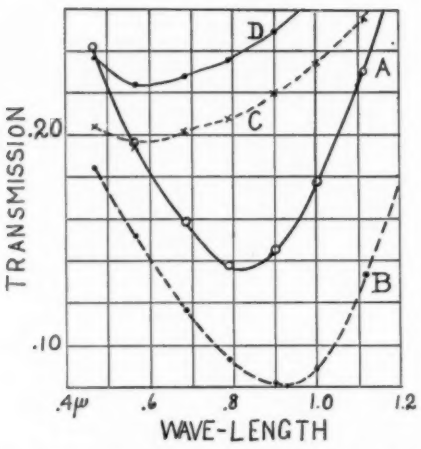


FIG. 6. Transmission curves showing shift of the minimum for a mosaic film upon changing the angle of incidence: *A*—dry TiO_2 mosaic film; angle of incidence = 0, *B*—dry TiO_2 mosaic film; angle of incidence = 48°, *C*—dispersed ZnS; angle of incidence = 0, *D*—dispersed ZnS; angle of incidence = 48°.

the curve *A* has been inverted (curve *B*) to give a qualitative representation of the variation of the light transmitted by a suspension as a function of λ/r. Curve *A* has three characteristic regions: (1) the region *R* where λ/r is large and where Rayleigh's law of scattering applies; (2) the region *D* where λ and r are commensurate and where Debye's theory applies; (3) the region *N* of nonselectivity where λ/r is small and where scattering is no longer a function of λ/r. Upon comparing the form of curve *B* Fig. 6, with that of curve *A* of Fig. 2, an unmistakable similarity is recognized. In view of this similarity

TABLE II.

PIGMENT	μ_2 PIGMENT	μ_2 CRYSTAL
S.W.L.	1.96	1.93
B.C.W.L.	2.11	1.94–2.09
ZnS	2.42	2.37
TiO_2	2.60	2.53

the present phenomena were, at first, interpreted on the basis of scattering.

Granting that the attempts made to verify, numerically, the consequences of the interference theory are but moderately successful, it is argued that "scattering" cannot be the explanation, since no theory of scattering presupposes the existence of a mosaic-pattern—a pattern whose

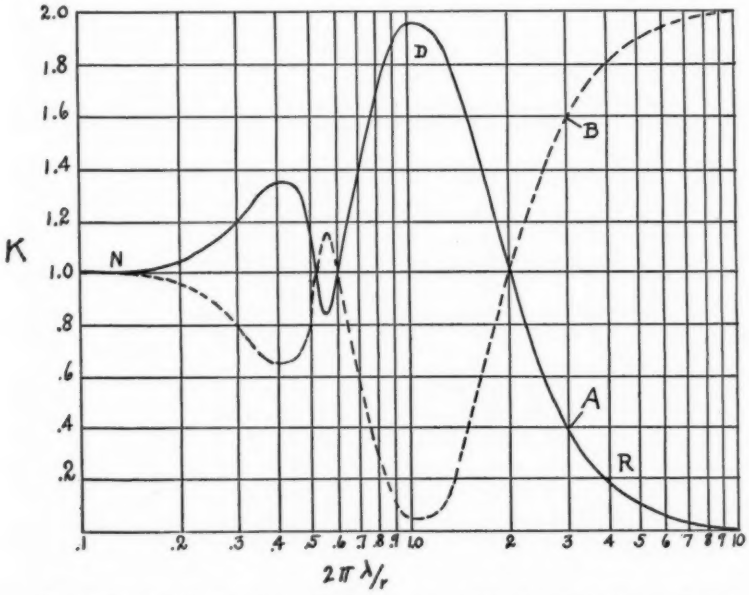


FIG. 7. Showing the Stratton and Houghton curve (*A*) of scattering by small water droplets ($\mu = 1.33$). The dotted curve *B* shows, qualitatively, the variation of transmission resulting from a change of λ/r, where λ = wave-length of light and r = radius of water-droplet.

existence is essential to the appearance of the deep transmission minimum and brilliant colors. It is admitted that the shallow minima shown in Fig. 6 curves *C* and *D* are probably of the Debye-Stratton and Houghton type, since in these cases the pigment particles were thoroughly dispersed—a condition ideal for scattering.

While the interpretation based on interference has been favored in the previous discussion, it is only fair to call attention to a number of disconcerting facts: (1) brilliant colors in transmitted light are sometimes observed over areas in which the pigment layer is more than one particle deep—in consequence of which the mosaic structure is not in evidence under the microscope. While this contradiction might be "explained" it is desired here only to state the fact. (2) According to the relation $(\mu-1)t=n\lambda/2$, transmission minima ought to appear at the wave-lengths λ, $\lambda/3$, $\lambda/5$, etc. corresponding to $n=1, 3, 5$ etc. The fact is that but one minimum has been observed. In consequence of some very careful measurements, it was found (curve *A*, Fig. 6) that, whereas the deep minimum $n=1$ for S.W.L. lay near 1.9μ, the next minimum, $n=3$, $\lambda=0.63\mu$, failed to make its appearance. To be sure, there is a real point of inflection in the curve near the correct wave-length (0.63μ) but, no minimum. A possible explanation is suggested by the circumstance that, for $n=1$ the minimum lies at $\lambda_1=1.9\mu$, i.e., $\lambda_1>D$ (where D, the diameter of the particle, is 0.76μ); for $n=3$, $\lambda_3=0.67\mu$, i.e., $\lambda_3<D$. This long argument is avoided in favor of statement of fact; (3) on the same mosaic film there are, occasionally, areas of different color; (4) when a bright lamp is viewed through a film showing colors, no halo of complementary color is in evidence.

In conclusion, it is to be emphasized that, for the explanation of the colors shown by mosaic films, interference has been favored over scattering only because the existence of a mosaic pattern is not a prerequisite for scattering. The principal purpose of this discussion is not to champion a theory, but to stimulate interest in a fascinating phenomenon.

A Note on the Color Temperature-Candlepower Characteristic of Tungsten Lamps*

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(Received November 3, 1938)

Tungsten lamps are now used very extensively in photographic sensitometry, and the wide range of exposures required for various materials makes necessary the accumulation of complete data on lamps of many sizes.

The characteristics of all tungsten incandescent lamps are similar in form, and in this note are described the average characteristics found for twenty lamps frequently used in this work.

From a study of the slope of the straight line, best representing the average candlepower-color temperature relation, it is concluded that the changes in candlepower and color temperature, resulting from a small change in voltage, should be about equally perceptible under good conditions of observation.

IN THE application of tungsten lamps to a variety of sensitometric problems in photography, color temperature and the candlepower are generally the first lamp characteristics to be fixed by the test requirements. The color temperature may be fixed by established practice in testing a given kind of photographic material or, in the case of a new material, by the use for which it is intended.

When color temperatures, higher than those conveniently attainable by the use of unfiltered tungsten lamps, are required, standardized blue filters such as those of the Davis-Gibson type may be used.

The candlepower required is determined by the speed of the material to be tested and the distance at which the lamp can be set from the exposure plane in the sensitometer. The differences in the sensitivity of materials made for various purposes are very great, and it is therefore necessary to study the characteristics of lamps of many different kinds and sizes over a wide range.

It is found that the candlepower-color temperature relation of tungsten lamps, even of those of widely different sizes and construction, has very much the same form. Differences exist which are too large to be ignored in the final calibration of a lamp, but a general curve representing the average characteristics of a variety of lamps is very useful in selecting a suitable lamp for a particular application.

A special graph paper in which the ordinates are in logarithmic candlepower units and the abscissas are in reciprocal temperature units has been found very useful in graphically representing the candlepower-color temperature characteristics. On such a web, this characteristic curve, as has been indicated by Nutting[1] and by Pirani and Miething,[2] is very nearly a straight line. In Fig. 1 is shown the average characteristic curve for twenty lamps of quite different constructions which have been measured from time to time. The average currents and voltages have also been plotted against the color temperature on the reciprocal scale. These show much greater curvature than does the candlepower characteristic.

It has been found that the candlepower-color temperature locus for some lamps is concave upward and for others it is concave downward. The average relation may be closely represented by the straight line as shown in Fig. 1. In Fig. 2 are shown the candlepower-color temperature characteristic curves for tungsten,[3] and for a black body as calculated from the empirical formula.[4]

$$\log_{10} CP = A - \frac{11{,}544}{T} + \frac{844{,}200}{T^2}. \qquad (1)$$

* Communication No. 701 from the Kodak Research Laboratories.

[1] P. G. Nutting, "Luminosity and Temperature," Bull. Nat. Bur. Standards **6**, 337–46 (1909–10).

[2] Marcello Pirani and Hildegard Miething, "Strahlungsenergie, Temperatur, und Helligkeit des schwarzen Körpers," Verhandlungen der deutschen physikalischen Gesellschaft, **17**, 219–39 (1915).

[3] W. E. Forsythe and A. G. Worthing, "Properties of Tungsten and the Characteristics of Tungsten Lamps," Astrophys. J. **61**, 146–85 (1925).

[4] K. S. Weaver, "The Calculation of Filters for Color Temperature Conversion," J. Opt. Soc. Am. **26**, 339–42 (1936).

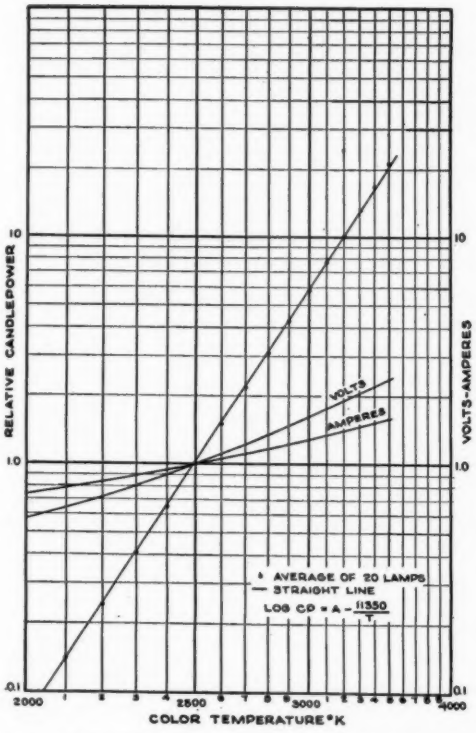

FIG. 1. Average color temperature, voltage, current and candlepower characteristic of twenty tungsten lamps, showing close approximation to linearity of the candlepower-color temperature characteristic.

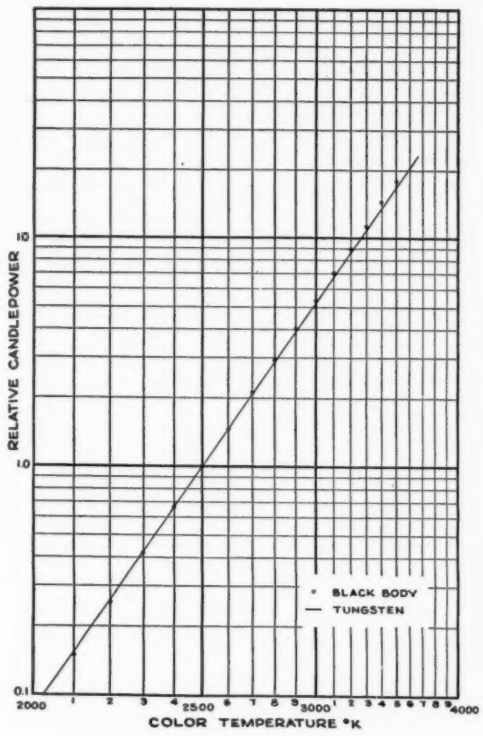

FIG. 2. Color temperature-candlepower relation for tungsten and the Planckian radiator.

In this equation, CP represents the candlepower brightness or lumen output, and A is a constant depending on the radiating area or size of the source.

Since all of these curves have been plotted on arbitrary scales of candlepower, current and voltage, they show only the manner in which the relative values of these variables change with the color temperature. For use in selecting lamps, a collection of complete curves, made up from laboratory test data, is kept for reference and by its use it is generally possible to select at once a lamp of the desired candlepower and color temperature. In case a new type of lamp is under consideration, measurement of the candlepower at one color temperature is sufficient to indicate, by use of the average characteristic, whether it meets the requirements.

The average candlepower-color temperature characteristic shown in Fig. 1 may be represented by

$$\log_{10} CP = A - \frac{13{,}000}{T} + \frac{2.061 \times 10^6}{T^2}, \qquad (2)$$

and the straight-line locus for tungsten lamps shown in Fig. 1 by

$$\log_{10} CP = A' - 11{,}350/T. \qquad (3)$$

EXPONENTIAL FORMS

In cases where calculation of the relative change in lamp characteristics over a limited range is sufficient, exponential expressions are often used by the lamp manufacturers and test laboratories.[5, 6]

[5] Francis E. Cady and Henry B. Dates, (editors), *Illuminating Engineering for Students and Engineers* (John Wiley and Sons Inc., New York, 1925), First edition, p. 106.

[6] L. E. Barbrow and S. J. Franklin Meyer, "Characteristic Equations of Vacuum and Gas-Filled Tungsten Lamps," National Bur. Standards J. Research **9**, 721–32 (1932).

These take the following form:

$$CP_1/CP_0=(I_1/I_0)^a=(V_1/V_0)^b,$$

in which CP_0, I_0 and V_0 are corresponding values of candlepower, current and voltage at some selected reference point corresponding, for example, to the normal or rated values, and CP_1, I_1 and V_1 are corresponding values at another voltage. The exponents a and b are not, in general, constant over wide ranges; consequently, different values are required not only for different lamps but for different operating temperatures.

Relation of the color temperature characteristic to candlepower by an expression of the form:

$$CP_1/CP_0=(T_1/T_0)^x \text{ has been used.}^{1,2}$$

The value of x, however, varies quite rapidly with the temperature. A form applicable over a wider range is obtained from Eq. (2).

$$\log_{10}\frac{CP_1}{CP_0}=13{,}000\left(\frac{1}{T_0}-\frac{1}{T_1}\right)+2.061\times10^6\left(\frac{1}{T_1^2}-\frac{1}{T_0^2}\right). \quad (4)$$

or

$$\frac{CP_1}{CP_0}=10^{13{,}000(1/T_0-1/T_1)+2.061\times10^6(1/T_1^2-1/T_0^2)}. \quad (5)$$

Similarly, the simplified form, Eq. (3) leads to

$$CP_1/CP_0=10^{11{,}350(1/T_0-1/T_1)}. \quad (6)$$

These equations are similar in form to certain ones given by Nutting[1] and others for black-body radiation.

The value of the exponent in Eq. (6) which represents the straight-line tungsten curve of Fig. 1, may be obtained by differentiating (2) and substituting 2500°K for T in the result. That is, the straight-line tungsten characteristic shown in Fig. 1 has the same slope as that of the average characteristic at 2500°K, also shown in Fig. 1. The value of this exponent for other temperatures is calculated by the substitution of those temperatures in the same differential equations.

Table I gives, for a series of values of T, the exponents a and b, controlling the current and voltage relation, and c, the exponent of Eq. (6) controlling the color temperature-candlepower characteristic. Those values are the average for the twenty lamps whose characteristics are shown in Fig. 1.

The ratio, b/a, is practically independent of temperature and equal to 0.542. The lamps used included several sizes of projection lamps, Photoflood, auto headlight, and several of the small automobile lamps, and two special lamps made for the II-b type sensitometer. Such data will, of course, vary somewhat from lamp to lamp, so that they must be considered more as an illustration of the color-temperature characteristic than as applicable to any particular type of lamp. For making a selection of a suitable lamp, they are generally adequate for use up to the point of final calibration.

A comparison of the curve for tungsten lamps (Fig. 1) with that for tungsten (Fig. 2) shows a difference in slope. This is attributed to the fact that the effect of the filament leads and supports, present in lamps, has been eliminated in the Forsythe and Worthing data for metallic tungsten in the form of straight wires. The cooling effect of the supports and leads in actual lamps modifies both the candlepower and the color temperature; the presence of gas in most lamps and the coiling of the filament also must have their effect. The net result is that the change of candlepower with color temperature is greater in the case of the average tungsten lamp.

TABLE I.

T	a	b	c
2000	9.87	5.35	10,940
2100	9.26	5.02	11,040
2200	8.71	4.72	11,130
2300	8.20	4.44	11,210
2400	7.72	4.18	11,280
2500	7.29	3.95	11,350
2600	7.00	3.79	11,410
2700	6.77	3.67	11,470
2800	6.62	3.59	11,530
2900	6.50	3.52	11,580
3000	6.38	3.46	11,630
3100	6.33	3.43	11,670
3200	6.28	3.40	11,710
3300	6.22	3.37	11,750
3400	6.18	3.35	11,790
3500	6.14	3.33	11,820

The Photometric Work

The photometry of tungsten lamps over such a wide range of color temperatures required settings with large color differences in some cases. Two observers were used whose eyes were known to have nearly average color and brightness perception. The readings were taken by the equality of brightness method, using a Lummer-Brodhun photometer. These observers, both of whom have had considerable experience in such work, obtained good precision with the maximum color differences found and agreed within about four percent with each other.

As a check on the readings at the highest and lowest temperatures, a yellow color-temperature conversion filter was calibrated spectrophotometrically, its integral transmission at several color temperatures was calculated, and it was then used to reduce the large color differences of the comparison field. The results so obtained agreed very well with those obtained with the full color difference in the comparison field.

Sensibility to Color Temperature

From the relation between candlepower and color temperature given by the straight-line Eq. (3), it follows that a change of constant percentage in candlepower corresponds very closely to a constant change in reciprocal color temperature. Since, over a wide range of candlepower and color temperature, the sensibility to brightness change, $\Delta I/I$, is nearly constant,[7] and the sensibility to reciprocal color temperature change is nearly constant,[8] we find from Eq. (3) that, as the voltage of a lamp is changed, the sensibility to the resulting brightness change and the sensibility to the resulting color temperature change are in a constant ratio.

Table II.

T	ΔT	T	ΔT
2000	1.5	2800	3.1
2100	1.7	2900	3.3
2200	1.9	3000	3.5
2300	2.1	3100	3.7
2400	2.3	3200	4.0
2500	2.5	3300	4.3
2600	2.7	3400	4.5
2700	2.9	3500	4.8

Although sensibility to such changes shows considerable variation with different equipment and observers, enough work has been done to determine fairly well what can be expected under good conditions of observation. From the average slope of the candlepower-color temperature curve, we determine that a change in candlepower of one percent corresponds to a color temperature change of 0.39 microreciprocal degree. Judd[9] has found that, under various conditions of observation, the probable error of a single setting in color matching ranges from about 0.27 to 1.0 microreciprocal degree. This corresponds to 0.7 to 2.5 percent in light output. The lower figure (0.7) may be taken as approximately the probable error in a single photometric setting under the best conditions; we may conclude, therefore, that the sensibility of the eye to change in light output when the voltage of a tungsten lamp is varied is about the same as the sensibility to the corresponding change in color temperature.

The apparent greater facility in making a photometric balance is due to the simpler mechanical movements generally required. In color matching, it is of paramount importance to select rheostats for the lamp control which work smoothly and are neither too fine nor too coarse in adjustment. A photometric balance may generally be approached by infinitesimal steps, a fact which is of great importance in obtaining precision. Most rheostats work only in finite steps and unless the size of these steps is carefully chosen, the sensibility of the whole operation of making a setting is very much reduced.

Table II gives, for the color temperature range 2000°K–3500°K, the change in temperature (ΔT) in degrees Kelvin for a one percent change in candlepower for tungsten lamps.

[7] Jacinto Steinhardt, "Intensity Discrimination in the Human Eye. I. The Relation of $\Delta I/I$ to Intensity," J. General Physiology **20**, pp. 185–209 (No. 2, Nov. 20) (1936).

[8] Irwin G. Priest, "A Proposed Scale for Use in Specifying the Chromaticity of Incandescent Illuminants and Various Phases of Daylight," J. Opt. Soc. Am. **23**, 41–5 (1933).

[9] Deane B. Judd, "Precision of Color Temperature Measurement under Various Observing Conditions; A New Color Comparator for Incandescent Lamps," National Bur. Standards J. Research **5**, 1161–77 (1930).

Some Tests on Radiation-Mixing Enclosures

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(Received October 24, 1938)

SMALL spherical enclosures are often used in photometers of the photoelectric type, their function being to mix the radiation from two sources. Unfortunately, however, the introduction of any such diffusing device greatly reduces the photo-cell current because of absorption of radiant energy by the coating of the enclosure.

In the design of a photoelectric flicker photometer,[1] therefore, the loss of radiant energy in the spherical enclosure must be considered, and the sphere must be designed to reduce this loss to a reasonable value while still giving satisfactory diffusion. The theory of the integrating sphere with openings in it is well known.[2] But theory indicates that absorption of radiant energy in the sphere can be kept within satisfactory limits only by the use of very small enclosures where an appreciable part of the total spherical surface is taken up by openings. Under these circumstances, the device tends to lose all similarity to the theoretical sphere, and one begins to doubt if the predictions of theory have any relation whatever to actual fact.

Conditions are further complicated by the desirability of using cylinders or cubes instead of spheres, and by the possibility of introducing the photo-cell, with shields, into the enclosure. A theoretical attack on the actual case appeared hopeless, so the problem was investigated experimentally, the work being done in the Illuminating Engineering Laboratories of Massachusetts Institute of Technology. Spheres and cubes of various sizes were tested with various wall coatings and with the photo-cell in various positions, to determine the best practical arrangement and to see if the theory gave a useful approximation to the experimental results.

2. THEORY OF THE INTEGRATING SPHERE

The theory of the integrating sphere containing openings is based on the well-known fact that any perfectly diffusing, luminous element of the sphere produces uniform irradiation of the entire spherical surface. This relation, which in general holds only for *spherical* enclosures, allows a very simple application of the principle of conservation of energy, leading directly to the final equation. The following derivation is similar to that of Hardy and Pineo, but differs in several respects, notably in the use of irradiation ratio rather than flux ratio. The assumptions are:

(1) Assume that a true sphere is used and that the diffusing windows as well as the photo-cell sensitive surface are parts of a spherical surface.

(2) Assume that the inside surface of the sphere is perfectly diffusing* and is of uniform reflection factor throughout the portion not taken up by the openings.

(3) Neglect the effect of the glass envelope of the photo-cell.

(4) Neglect the reflection of radiant energy at the sensitive surface of the photo-cell.

(5) Assume that the radiant energy is homogeneous of wave-length λ.

(6) Assume that the entrance windows are perfectly diffusing.

Let A_1 = area of one entrance window (two such openings are used)
A_2 = area of exit aperture
S = total area of sphere, including openings
ρ_1 = spectral reflection factor of opal glass at wave-length λ (for diffused radiation falling on clear side of glass)
ρ_2 = spectral reflection factor of sphere wall at wave-length λ (for diffused radiation)
τ = spectral transmission factor of opal glass at wave-length λ (for parallel rays incident on opal side)
G_1 = irradiation[3] of opal glass (watts/cm² of homogeneous radiation)
G_2 = irradiation of sphere wall (watts/cm² of homogeneous radiation).

[1] "The Design of Photoelectric Flicker Photometers," a forthcoming paper by the authors, gives additional information.

[2] See Hardy and Pineo, "The Errors due to the Finite Size of Holes and Sample in Integrating Spheres," J. Opt. Soc. Am. **21**, 502 (1931).

* Follows cosine law.

[3] The notation is in accordance with Moon, *Scientific Basis of Illuminating Engineering* (New York, 1936). The integrating enclosures considered in the paper are fitted

The radiant energy entering the sphere per second is

$$G_1A_1\tau.$$

The radiant energy lost through the openings per second is

$$G_2[2A_1(1-\rho_1)+A_2]$$

and the radiant energy absorbed by the sphere wall per second is

$$G_2(1-\rho_2)(S-2A_1-A_2).$$

Thus, by the principle of conservation of energy,

$$\frac{G_2}{G_1}=\frac{\tau}{(S/A_1)(1-\rho_2)+[2(\rho_2-\rho_1)+(A_2/A_1)\rho_2]}. \quad (1)$$

For given areas of openings and given reflection factors, the term in the brackets is a constant, and G_2/G_1 increases as the area S is decreased.

If, for homogeneous radiation, the photo-cell current i is directly proportional to G,

$$\frac{i_2}{i_1}=\frac{\tau}{(S/A_1)(1-\rho_2)+[2(\rho_2-\rho_1)+(A_2/A_1)\rho_2]}, \quad (2)$$

where i_2 = photo-cell current when the integrating enclosure is used and i_1 = photo-cell current when the cell replaces the sphere entrance window and is directly exposed to the radiation.

If an opaque shutter is employed between the opal glass and the sphere openings, and if the shutter is black, a slight modification must be made in Eq. (2). The shutter is arranged so that when one of the entrance openings is fully open the other is closed,[1] and the total area of opal glass that can be seen from the inside of the sphere is always A_1 instead of the previous value of $2A_1$. Eq. (2) then becomes

$$\frac{i_2}{i_1}=\frac{\tau}{\frac{S}{A_1}(1-\rho_2)+\left[2\left(\rho_2-\frac{\rho_1}{2}\right)+\frac{A_2}{A_1}\rho_2\right]}. \quad (3)$$

The ratio (i_2/i_1) appears to be a good criterion for use in many photoelectric flicker photometers.[1] The maximum possible current is obtained by exposing the cell directly; but when, for various reasons, an integrating sphere is necessary, the current is reduced by the ratio (i_2/i_1).

with windows of flashed opal glass, which diffuse the light from the sources that are compared by the photo-cell.

The foregoing derivation assumes the use of homogeneous radiation; but it applies equally well to any spectral distribution of radiant energy provided the materials are nonselective (ρ and τ independent of λ). Selective materials cause a change of spectral distribution, which is emphasized by multiple reflections and which introduces an additional uncertainty. Since the purpose of the tests was to simulate actual photometric conditions rather than to produce the ideal conditions of theory, an incandescent lamp was used as the source. All materials were slightly selective, but we arbitrarily chose values of ρ and τ corresponding to visual evaluation.

3. Apparatus

The enclosures built for the tests consisted of four cubes, two spheres, one hemisphere, and one circular cylinder. The cubes were made of 1.6-mm sheet brass assembled in frames of 13×13-mm brass bar. The sizes ranged from 30.5 cm (12 in.) to 7.6 cm (3 in.) on a side, as shown in Fig. 1. Each sphere was made of two metal hemispheres with a heavy clamping ring. The cylinder consisted of a section of brass tubing with flat ends. Each enclosure was provided with two entrance windows (which would ordinarily be used for the entrance of the two beams of light being compared by the photocell) and one exit opening. Flashed opal glass was used in the entrance windows and was clamped as shown in Fig. 2.

The white paint was Muresco, a water paint giving a matt surface with spectral reflection factor ranging from 0.62 at 0.40μ to 0.84 at 0.70μ. The gray paint was obtained by mixing lamp black with a matt white oil paint. The reflection-factor curve showed a smooth variation from 0.50 at 0.40μ to 0.42 at 0.70μ. The MgO coating was applied by the method developed by Howard* of the Electrical Engineering Research Laboratory, Massachusetts Institute of Technology. Magnesium oxide powder was mixed with distilled water, and a number of coats were sprayed onto the surface. Each coat was baked after spraying. The final finish was given by

* We wish to thank Dr. G. S. Brown and Mr. J. H. Howard for their advice on the MgO coatings. Most of the data on reflection factor were obtained by use of the Hardy color analyzer, for which data we are indebted to Professor A. C. Hardy and his associates.

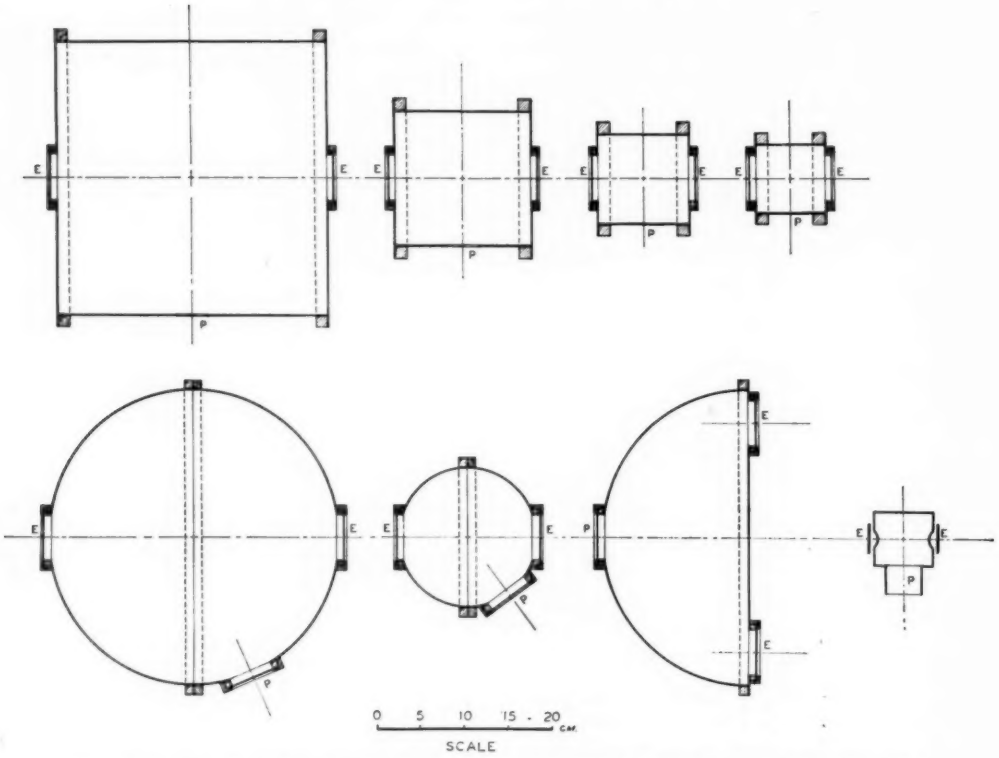

FIG. 1. Cross sections of enclosures. E = opening for entrance of light; P = opening for photo-cell.

smoking with magnesium oxide. The result is much more permanent and less subject to flaking than when a painted surface is used as the base for the smoking. After standing in the laboratory for a week, the surface was found to have a reflection factor of 0.96, which was essentially uniform throughout the visible region.

The photo-cell was a Western Electric 5-A vacuum cell of the Cs-O-Ag type, responding to wave-lengths from approximately 0.3 to 1.2μ. Arrangements were made so that it could be used in the following positions: (a) outside the exit openings, as close as possible to the opening; (b) projecting into the enclosure so that the sensitive surface was inside, but the black base of the cell was outside; (c) entirely within the enclosure; (d) entirely within the enclosure, but with the back of the cell painted white. In the cubes, the cell was not introduced in the center of a side but slightly displaced (Fig. 2) so that little or none of the direct light from the entrance windows could affect it. A similar arrangement was used with the spheres and with the cylinder. In a few tests (d), the back, end and base of the cell were heavily coated with white paint ($\rho = 0.77$).

The source used in all tests was a 500-watt projection lamp operated at reduced voltage to give a color temperature of approximately 3000°K. Readings were taken at distances of 0.5, 1, 2 and 4 meters from lamp filament to entrance window and the results were averaged. Corresponding readings were taken with the bare photo-cell in the position usually occupied by the entrance window. Photo-cell currents were measured by means of a Type R galvanometer and Ayrton shunt.

The effects of the following four variables were investigated:

1. Form of enclosure: (a) cube, (b) sphere, (c) hemisphere, (d) cylinder.
2. Size of enclosure.

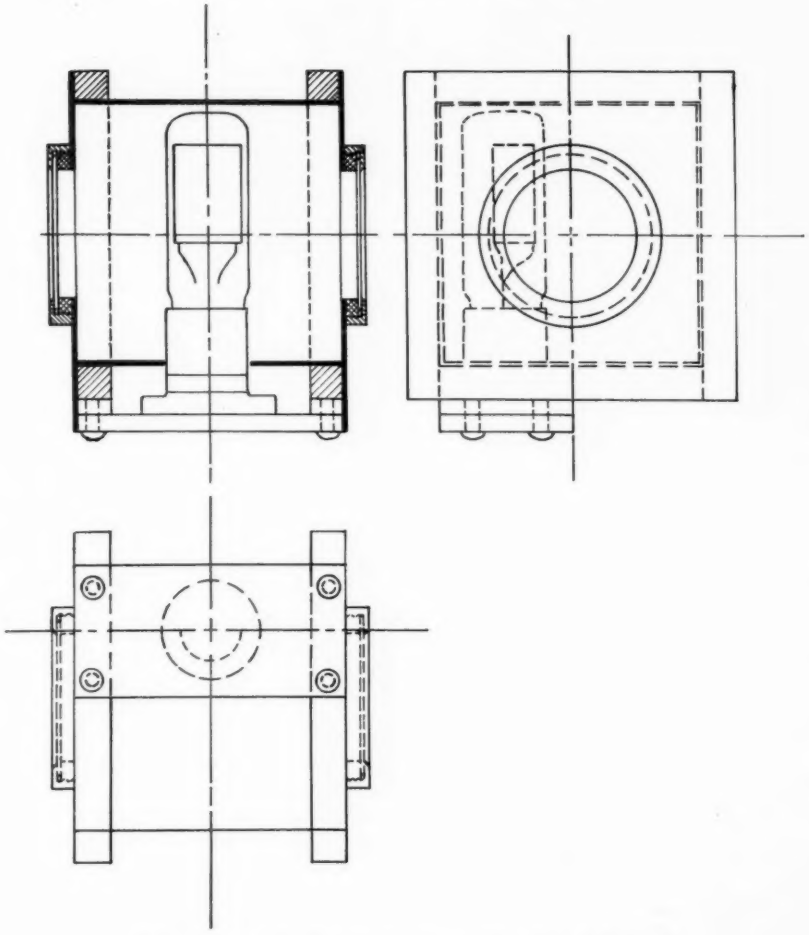

FIG. 2. A cube, showing construction and location of photo-cell.

3. Coating of enclosure: (a) white paint, (b) gray paint, (c) MgO.
4. Cell position: a, b, c, d, as previously enumerated.

4. RESULTS

The experimental results are summarized in Table I. Each value is the average of a number of readings and represents the ratio of the photo-cell current (i_2) when the cell is within the enclosure to the current (i_1) when the cell is exposed directly to the radiation. As would be expected, the ratio is highest with the MgO coating and is progressively less as the reflection factor of the coating is reduced. Table I shows also that the ratio rises as the size of the enclosure is decreased, which is in agreement with theory.

With the painted coatings, the current is least when the cell is outside the enclosure and greatest when the cell is completely inside. The arrangement, in order of increasing current, is cell outside, painted cell inside, cell half in, cell completely in. Thus, despite the fact that the black base of the cell and the glass envelope absorb energy, best results are obtained with the *unpainted* cell completely inside the cube or sphere. With the MgO coating, on the other hand, best results are obtained with the cell only half in.

5. Comparison with Theory

The results of Table I are direct experimental ratios and no use has been made of values of reflection factor or transmission factor. In comparing the experimental ratios with ratios predicted by Eq. (2), however, one must have values of ρ_1, ρ_2, and τ. The data given in Table II were substituted in Eq. (2), except with the cylinder, where Eq. (3) was used. The cylinder was a part of a complete flicker photometer[1] and had a shutter between the opal glass and the cylinder openings.

The comparison of calculated and experimental values is given in Table III. Two experimental conditions are included, one for the cell outside the enclosure and the other for the cell completely inside. In every case, the experimental photo-cell current obtained with the cell outside the enclosure is less than the calculated current, the ratio being approximately 1 : 2. The currents obtained for the cell within the enclosure are usually somewhat nearer the calculated values, and in a number of cases the difference between calculated and experimental values is less than ten percent.

A noteworthy result is that all the forms of enclosure seem to behave in the same way. Eqs. (2) and (3) were derived for spheres only; yet if they are used for other types of enclosure, the total area S being taken in all cases as the actual internal area of the cube, hemisphere, or cylinder, then the calculated (i_2/i_1) is in agreement with experiment.

The agreement, it is true, is far from a precise one; but on the basis of all the peculiar assumptions made in the theory, the agreement is surprisingly good. Assumption 1 (Section 2 of this paper) is obviously not satisfied, since neither entrance windows nor photo-cell are parts of a spherical surface. With the cell outside the sphere, the shielding action of the exit aperture tends to reduce the photo-cell current, while radiant energy reflected from cell (Assumptions 3 and 4) is lost. One might expect the values of i_2/i_1 to be low, as they turned out to be.

But if the cell is within the enclosure, there is a possibility that the readings will be higher because of interception by the cell of the specular component of reflected radiation (Assumption 2) and by multiple reflections between cell and sphere (Assumptions 3 and 4).

It should be pointed out, also, that the computed values are greatly dependent on the

Table I. *Summary of experimental results.*

Nominal Size	Cell	i_2/i_1 MgO	White	Gray
Cubes				
30.5 cm.	Out (*a*)	0.015	0.0057	
	Painted (*d*)	——	0.0091	
	½ (*b*)	0.048	0.013	
	In (*c*)	0.039	0.014	
15.2	Out (*a*)	0.048	0.018	0.0062
	Painted (*d*)	——	0.029	——
	½ (*b*)	0.115	0.037	0.015
	In (*c*)	0.099	0.042	0.017
10.2	Out (*a*)	0.071	0.030	0.014
	Painted (*d*)	——	0.038	——
	½ (*b*)	0.134	0.058	0.028
	In (*c*)	0.111	0.062	0.030
7.6	Out (*a*)	0.102	0.052	
	Painted (*d*)	——	0.045	
	½ (*b*)	0.159	0.073	
	In (*c*)	0.145	0.081	
Spheres				
32.8	Out (*a*)	0.034	0.012	
	Painted (*d*)	——	0.018	
	In (*c*)	0.069	0.028	
14.8	Out (*a*)	0.105	0.033	
	Painted (*d*)	——	0.037	
	In (*c*)	0.131	0.069	
Hemisphere				
32.8	Out (*a*)	0.046	0.015	
	Painted (*d*)	——	0.020	
	In (*c*)	0.080	0.032	
Cylinder				
6.3	½ (*b*)	0.024	——	

Table II. *Data used in calculations.*

Quantity	Cubes	Spheres	Hemisphere	Cylinder
τ	0.55	0.55	0.55	0.55
ρ_1	0.33	0.33	0.33	0.33
ρ_2 MgO	0.96	0.96	0.96	0.95
ρ_2 White	0.77	0.77	0.77	——
ρ_2 Gray	0.45	——	——	——
A_1 (cm²)	20.3	20.3	20.3	2.22
A_2 (cm²)	9.6	20.3	20.3	11.4

TABLE III. *Comparison of calculations with experimental results.*

Nominal Size	Actual S Cubes	ρ_2	i_2/i_1 Calc.	i_2/i_1 Exp., Cell out	i_2/i_1 Exp., Cell in
30.5 cm	5540 cm²	0.77	0.0086	0.0057	0.014
		0.96	0.044	0.015	0.039
15.2	1395	0.45	0.014	0.0062	0.017
		0.77	0.032	0.018	0.042
		0.96	0.123	0.048	0.099
10.2	620	0.45	0.032	0.014	0.030
		0.77	0.067	0.030	0.062
		0.96	0.188	0.071	0.111
7.6	334	0.77	0.109	0.052	0.081
		0.96	0.232	0.102	0.145
Spheres					
32.8	3360	0.77	0.014	0.012	0.028
		0.96	0.062	0.034	0.069
14.8	670	0.77	0.060	0.033	0.069
		0.96	0.155	0.105	0.131
Hemisphere					
32.8	2520	0.77	0.018	0.015	0.032
		0.96	0.077	0.046	0.080
Cylinder					
6.3	171	0.95	0.055	——	0.024

values of ρ_2 used in Eq. (2). With $\rho_2=0.50$, an error of 0.01 in ρ_2 will cause an error of less than 0.02 i_2/i_1, but an error of one percent between 0.98 and 0.99 in the reflection factor of MgO* might cause an error of almost 0.50 i_2/i_1 in the computed value of (i_2/i_1). The radiation was by no means homogeneous (Assumption 5), which introduces additional uncertainty in the values of ρ_2 to be used in the computations. As stated previously, our purpose was to test the enclosures under practical operating conditions, where the radiation is usually nonhomogeneous and where the important questions to be decided are best size of enclosure, best shape, order of magnitude of (i_2/i_1).

* Note that the Hardy color analyzer does not give absolute values of reflection factor but values on the basis of a certain standardized MgO surface. The actual reading for our spheres was 0.98, which was then corrected for a 0.98 standard, giving a final value of $\rho_2=0.96$. The value of 0.98 for the standard is the most reliable value obtainable at present, but it may be in error by as much as one percent.

6. Conclusions

The small integrating enclosure is an effective means of mixing radiations in photoelectric photometers. The reduction in photo-cell current caused by the introduction of a sphere, however, is calculable only on the basis of several wild assumptions; while for any form of enclosure other than a sphere, containing arbitrarily spaced openings, no theoretical treatment has ever been made. Data obtained with spheres, cubes, a hemisphere and a cylinder allow a study of the validity of the theoretical formula and a determination of the best arrangement for practical work. *The results show that, for approximate calculations, the theory of the integrating sphere (with openings) may be applied not only to the sphere but also to the cube, the hemisphere and the cylinder.* The experimental value of (i_2/i_1) is generally within ±50 percent of the calculated value.

The best coating appears to be MgO, which should preferably be in a dust-proof enclosure to reduce deterioration. *The most convenient form of enclosure is ordinarily the cube.* It is simplest to construct and allows greatest freedom in the placement of the openings. The mixing action of the sphere may be slightly superior to that of the cube, though we observed no such effect and believe that the cube, hemisphere and cylinder are all satisfactory forms.

The photo-cell current increases as the size of enclosure is decreased, a practical limit being fixed by the sizes of openings and cell. A convenient size of cube is 10 to 15 cm on a side. For best results, the cell should be placed with its sensitive surface within the enclosure but so oriented that no direct radiation falls on it. The cell should be symmetrically placed with respect to the two entrance windows. A large percentage loss of radiant energy by absorption in the walls of the enclosure seems to be inevitable. By employing enclosures of small size and by using MgO, however, values of $i_2/i_1=0.10$ are obtained without difficulty. That is, under good conditions the photo-cell current will be approximately ten percent of its value with the integrating enclosure omitted.

Measurement of Activation and Decay of Luminescent Zinc Silicate

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(Received September 29, 1938)

A transmission phosphoroscope is described that gives information on the activation and decay rates of luminescent powders, and indicates the relative amounts of fluorescent and phosphorescent light.

THE phenomenon of luminescence exhibited by certain substances when exposed to ultraviolet light, x-rays or cathode rays is composed of a fluorescent component having a decay period of less than 10^{-5} sec. and a phosphorescent component of a much longer decay time. The apparatus described below was designed to measure the rates of activation and decay of certain luminescent compounds called Lenard phosphors. These substances owe their activity to the inclusion of very small amounts of metallic impurity atoms in the normal crystal structure and were intensively studied by Lenard[1] and his pupils.

Measurements of phosphorescence date back to the original work of Becquerel.[2] These and more recent investigations were generally confined to determining the rates of decay of the phosphorescent light. Such measurements are readily made on certain sulphides[3] where the time of observation is of the order of seconds or minutes. When substances such as luminescent zinc silicate (synthetic willemite) are investigated, the extremely rapid rates of decay necessitate modifications in conventional methods of measurement. It is also interesting to study the rates of activation as well as the rates of decay and to estimate the relative amounts of fluorescence and phosphorescence.

A transmission type phosphoroscope, shown diagrammatically in Fig. 1 was designed to yield this data. A glass cylinder 5″ in diameter and 3″ high had its outer surface uniformly coated with fluorescent material. The cylinder was waxed to a brass plate mounted on the end of a motor shaft. A d.c. motor was selected so that its speed could be varied over a considerable range. The actual speed of the rotating cylinder was obtained before and after a set of data were obtained with a revolution counter and stop watch. The drum was irradiated with ultraviolet light from a "window lamp" in which a low pressure mercury discharge produced a copious and steady amount of resonance radiation of 2537A wave-length. The "window" is an internally blown bubble of thin highly transmitting glass to reduce absorption of ultraviolet light to a very low value. About 50 percent of the total radiant energy is at 2537A. The light from this lamp was constant to within a few percent after temperature equilibrium had been established. The lamp was operated on d.c. to eliminate stroboscopic effects.

A small caesium photo-cell was mounted inside the rotating cylinder in a housing with a narrow slit (2.5 mm×17 mm) that could be placed at any desired place along the circumference of the cylinder. The photo-cell was mounted as close to the inner surface of the glass cylinder as possible to include only the light from a narrow segment of the luminous band of

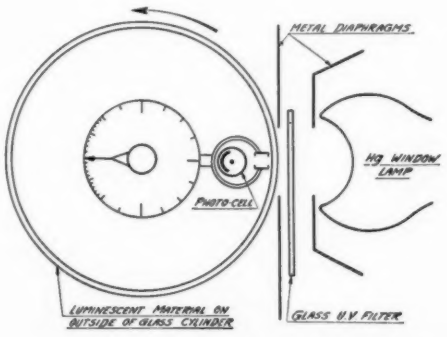

FIG. 1. Transmission phosphoroscope.

[1] Lenard, *Handbuch der Experimental Physik*, Vol. 23, Part 1 (1928).
[2] E. Becquerel, La Lumière **1**, 260 (1867).
[3] W. H. Byler, J. Am. Chem. Soc. **60**, 632 (1938).

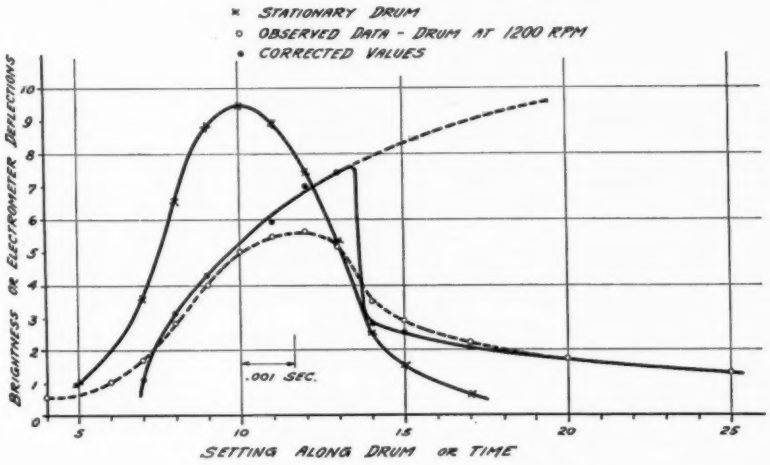
× STATIONARY DRUM
○ OBSERVED DATA - DRUM AT 1200 RPM
• CORRECTED VALUES
BRIGHTNESS OR ELECTROMETER DEFLECTIONS
.001 SEC.
SETTING ALONG DRUM OR TIME

FIG. 2. Activation and decay of 2 $ZnO-SiO_2$: Mn.

phosphorescent light. Photo-cell currents were measured with a Compton electrometer.

Two metal diaphragms were placed between the ultraviolet lamp and the rotating cylinder to define the illuminated area on the glass drum. With wide rectangular openings in the metal diaphragms and a narrow slot in front of the photo-cell, one can obtain data for an activation curve by moving the photo-cell across the opening of the diaphragm in small steps. Over this region the stationary disk upon which the photo-cell housing rotates is divided into 80ths of a circle. To adequately cover this region 10 or 12 readings were taken. Visible light from the window lamp was separated from the fluorescent or phosphorescent light generated by the coating material by interposing a clear glass filter to absorb the ultraviolet radiation from the lamp. The difference in electrometer readings with and without the glass filter at any one setting is a measure of the luminescent effect. By moving the photo-cell along the circumference, electrometer readings indicate the rate of decay of the phosphorescent light.

Figure 2 illustrates the type of data obtained with the transmission phosphoroscope. The curve joining the crosses indicates the distribution of energy from the window lamp, and was obtained while the drum was stationary. Due to the non-uniformity of illumination across the diaphragm aperture, the resulting curve is peaked at the center. It would be desirable to start with illumination of uniform intensity, but to attain this condition the intensity of the ultraviolet radiations would be greatly reduced. The observed curve was transformed into one of uniform energy by applying factors to the ordinates to give a resulting flat top curve with parallel sides. The intensity of the ultraviolet light was that of the maximum recorded value at the center of the illuminated area, limited by the geometric shadow of the parallel sides of the diaphragm aperture. By applying these same factors to the data of the corresponding photo-cell settings obtained with the rotating drum, the observed points indicated as circles were transformed to the curve connecting the solid dots. This latter curve shows the rate of activation and the rate of decay of the synthetic willemite if the fluorescent material were exposed to a source of ultraviolet light of uniform intensity across the diaphragm opening. In this experiment the material attains only about 80 percent of the maximum possible activation before deactivation starts. Corrections are made for the scattered light of the penumbra shadow at the edges of the diaphragm, recorded as the sloping tails to the curve of the stationary drum. The activation curve extended beyond the measured values shows that about 0.01 sec. is required for complete activation of this luminescent material.

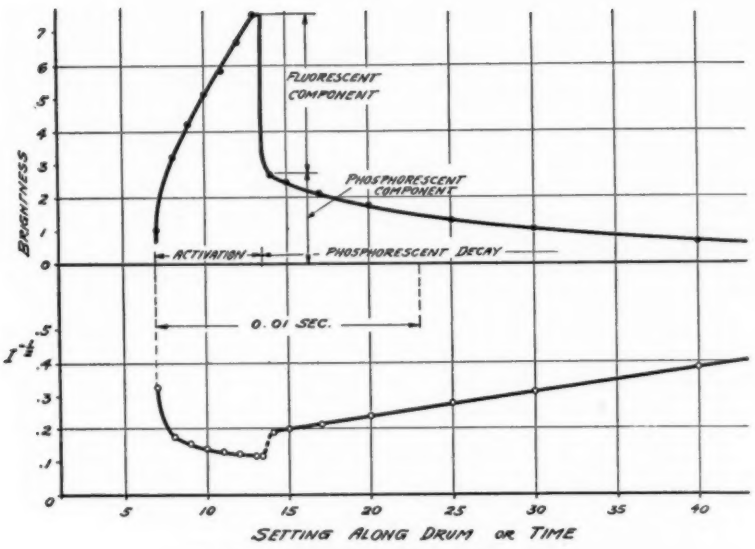

FIG. 3. Luminescence of 2 $ZnO-SiO_2$: Mn.

Nichols[4] and his associates found that by plotting the inverse square root of the brightness against time, one or more straight line segments were obtained. Replotting the data of Fig. 2 with $I^{-\frac{1}{2}}$ as ordinates a curve of the style shown in Fig. 3 is obtained. The upper curve of Fig. 3 is the same as the curve of solid dots in Fig. 2. It is plotted on the same time scale as the lower inverse curve to show the relationship between observed brightness values and the calculated inverse square roots of the brightness. The latter curve is a straight line over the circumference of the rotating drum or a time interval of about 0.05 second. Figs. 2 and 3 indicate the maximum intensity of illumination at the instant the source of illumination is removed. In this case about $\frac{2}{3}$ of the brightness of the powder was caused by fluorescence wherein the time of decay is less than 10^{-5} sec. and $\frac{1}{3}$ was caused by phosphorescence having, by comparison, a relatively long decay period.

[4] E. L. Nichols, H. L. Howes and D. T. Wilber, Phys. Rev. **12**, 351 (1918).

On Lithium Fluoride-Quartz Achromatic Lenses

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(Received October 15, 1938)

IN ADDITION to providing crystal stock to replace the rapidly diminishing supply of fluorite for use in extreme ultraviolet spectroscopy, the development of a large scale process for growing single crystals of lithium fluoride[1] had several objectives. One of these was to make possible the production of relatively inexpensive achromatic lenses suitable for use in the quartz-transmitted ultraviolet region of the spectrum, the desirability of which has often been mentioned.

The purpose of this paper is to discuss and demonstrate how favorably the optical constants of lithium fluoride combine with those of crystal quartz to form an achromatic lens covering a broad spectral range. As an illustrative example, we describe an air-separated doublet, of $f/10$, corrected for spherical aberration and approximately achromatic from 1800A* to 14,000A.

It is of interest to examine the data in Table I[2] to see how well lithium fluoride and quartz meet the conditions commonly imposed on optical materials which are to be used in making achromatic lenses.[3] These conditions are given below.

(1) The dispersion, $dn_1/d\lambda$, of the material of the positive element should be small. As is well known, the dispersion of lithium fluoride is unusually low in the visible and ordinary ultraviolet regions of the spectrum. The consequence of this is that a lithium fluoride lens possesses a relatively small variation in focal length with wave-length.

(2) The dispersion, $dn_2/d\lambda$, of the material of the negative element should be proportional to $dn_1/d\lambda$ for all wave-lengths. It follows from this that the λ_0's in the Hartmann dispersion formulas should be equal.

(3) The constants, ν_1 and ν_2, should be widely different. When this condition is satisfied, the focal lengths of the elements are long.

In the visible region the second condition is more nearly satisfied by the combination, lithium fluoride and quartz, than by the combination, fluorite and quartz. In the ultraviolet region fluorite is slightly superior to lithium fluoride in this respect, but the superiority is offset by the greater difference between the ν's of lithium fluoride and quartz.

Although better refractive index data are needed in order to make a more accurate comparison of the two combinations, it is evident that lithium fluoride is at least an excellent substitute for fluorite in achromatic combinations with quartz.

The calculated specifications of the doublet, which is intended to be used as a collimating lens, are given in Fig. 1. After an approximate design had been obtained algebraically, improvements were made by tracing the rays trigonometrically. The positive element (lithium fluoride) was

[1] D. C. Stockbarger, Rev. Sci. Inst. **7**, 133 (1936).
* For work in the Schumann region, within which the transmission of quartz drops to zero, we have designed and are now testing a combination of lithium fluoride and fluorite.
[2] F. H. Perrin, J. Opt. Soc. Am. **28**, 88 (1938).
[3] Hardy and Perrin, *The Principles of Optics*, Chapter VI.

TABLE I. *Optical constants.*

MATERIAL	n	$dn/d\lambda$	ν	n_0	c	λ_0
		Visible Region ($\lambda = 5890$A)				
Lithium fluoride	1.39177	-2.05×10^{-6}A^{-1}	98.4	1.38288	37.676A	1611.5A
Fluorite	1.43385	−2.35	95.4	1.42401	41.529	1681.3
Quartz (Ord. ray)	1.54426	−3.98	70.0	1.52710	73.551	1604.6
		Ultraviolet Region ($\lambda = 3610$A)				
Lithium fluoride	1.40133	-8.35×10^{-6}A^{-1}	21.9	1.38117	48.593A	1200.0A
Fluorite	1.44534	−10.32	19.2	1.42121	56.128	1284.5
Quartz (Ord. ray)	1.56347	−17.20	14.4	1.52401	90.207	1324.2

designed to have a minimum of spherical aberration; the negative element to achromatize the lens and to correct the residual spherical aberration. The six first-order internal reflections are all diverging and therefore do not produce flare in the image. No attempt has been made to correct for coma although correction would have been possible through increasing the spherical aberration and coma of the positive element and designing the negative element to correct both of them.

A quartz-lithium fluoride-quartz achromatic triplet has recently been calculated. This combination appears to offer the best solution of the spherical aberration and coma problem and is superior to the doublet in that the lithium fluoride element is protected by being enclosed. A test lens is now under construction.

The calculated performance curves of three doublets, including the one drawn in Fig. 1, are presented in Fig. 2. Of these, curve *C* is interesting since it indicates clearly the possibility of making lenses of lithium fluoride and quartz which are apochromatic within the normal working range of the spectrum. Curve *B*, which refers to the described doublet, is perhaps of even greater interest because it shows that chromatic

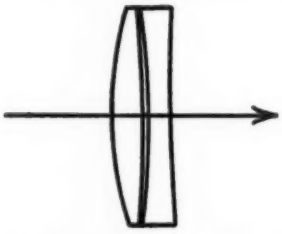

FIG. 1. Positive element, lithium fluoride. $R_1 = 17.0$ mm. $R_2 = -65.9$ mm. Negative element, quartz cut with lens axis parallel to optic axis. $R_3 = -39.4$ mm. $R_4 = 90.0$ mm. Diameter 10 mm. Focal length 100 mm.

aberration can be kept small over a long range of the spectrum.

To test the theoretical predictions and to demonstrate the usefulness of a lithium fluoride-quartz achromat, we have had a doublet built in the department optical shop. The design was essentially that of Fig. 1, although for practical reasons the focal length and diameter were increased to 250 mm and 25 mm, respectively. The achromatism was tested by replacing the slit of a small commercial quartz spectrograph by a virtual slit produced by focusing a reduced image of an auxiliary slit (magnification 1 : 3) on the plane of the spectrograph slit by means of the doublet. The spectrograph was in proper adjustment to give sharp lines throughout the spectrum before this replacement was made and no adjustments were changed during the tests. With the spectrograph slit widely opened, and hence acting merely as a baffle to reduce the entrance of stray

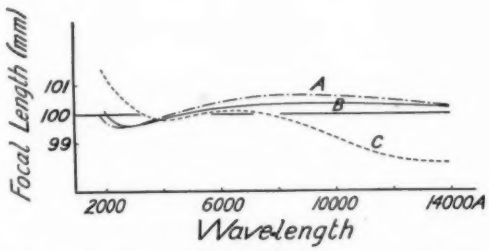

FIG. 2. Calculated variation in focal length with wavelength of three lithium fluoride-quartz doublets. Focal length of positive element at 5000Å: *A*, 35.9 mm; *B*, 34.4 mm; *C*, 32.7 mm. Curve *B* refers to the doublet shown in Fig. 1.

radiation, spectrograms of quartz mercury arc radiation were made with the auxiliary slit placed at different distances from the achromat. With this slit in the best position it was found possible to obtain photographs in which all lines from λ1942 to λ5790 appeared to the eye to be as sharp as in spectrograms made in the normal manner with a real slit. Doubtless depth of focus can account partially for this favorable result, but it cannot account for it entirely, as was proved by substituting first a crystal-quartz lens and then a lithium fluoride lens for the doublet. These lenses had approximately the same focal length and diameter as those of the doublet. With them only very narrow regions of the spectrum could be brought into focus with a single setting of the auxiliary slit distance. Portions of two spectrograms made with the quartz lens and one made with the doublet are reproduced in Fig. 3.

The reported tests, although only semi-quantitative, show clearly that lithium fluoride is suitable for combining with crystal-quartz to make achromatic lenses which are useful over broad ranges of the spectrum.

Professor A. C. Hardy and Dr. A. F. Turner

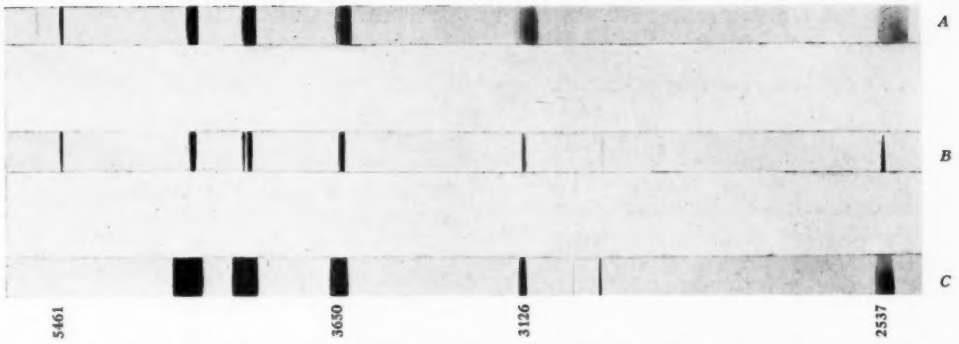

FIG. 3. Spectrograms showing effect of variation in focal length on sharpness of lines. *A* and *C* were made with a crystal-quartz lens. *B* was made with the lithium fluoride-quartz doublet.

helpfully discussed with us the results of the experiments. Mr. A. G. Hall carefully prepared the lens elements and assisted us in many ways during the tests.

A Densitometer Employing an Alternating Current Amplifier

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(Received November 4, 1938)

I. INTRODUCTION

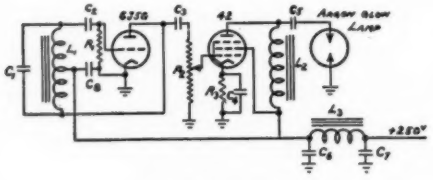
THE densitometer described in this paper is an application of the stable and reliable alternating-current amplifying circuit to the problem of measuring photographic densities. A glow lamp, actuated by an oscillator and power amplifier, is used to obtain the pulsating light, instead of the mechanical chopper that has been used in previous applications of this circuit. A circular area, $\frac{1}{8}$ inch in diameter, is measured, and densities are read directly from a calibrated attenuator.

II. CIRCUIT DESIGN

Figure 1 gives the circuit diagram of the oscillator, power amplifier and glow lamp assembly, and Fig. 2, the diagram of the photo-cell amplifier, attenuator and vacuum tube assembly. A 6J5G tube is used as oscillator and is operated at 225 cycles per second. This frequency is doubled by the two-plate glow lamp and photo-cell, so that the photo-cell amplifier operates at 450 cycles per second. It is therefore possible to use small grid coupling condensers to minimize the effect of noise and hum picked up from 60-cycle power lines in the laboratory, and to use small shunting condensers in the plate circuits of the high gain tubes in the amplifier, to decrease the effect of thermal noise in the photo-cell load resistor, and to suppress harmonics caused by the nonsinusoidal nature of the light from the glow lamp. A noise tested resistor is used as the photo-cell load. A type 42 tube is used as the power amplifier to supply the 2.5 watts necessary to actuate the glow lamp. An argon glow lamp is used, since most of the radiation from this lamp is at the blue end of the spectrum, to give a close approximation to photographic printing density,[1] as most of the common printing materials are sensitive only to radiation of wave-length shorter than about 5200A.

A type 868 photo-cell is used because of its high sensitivity at the blue end of the spectrum, as compared with other commercial cells of the caesium type.

In order to make it possible to measure small areas of high density, it is necessary for the amplifier to have a voltage gain on the order of 100,000. This is obtained by the use of two high gain stages, with type 6C6 tubes, and one stage with a gain on the order of ten, using a 6K6G tube. Since the output voltage of the first tube will be 10,000 times as great with density zero in front of the aperture as it will with density four, it is necessary to prevent overloading the grid of the second tube when measuring low densities. Measurement indicated that with the plates of the glow lamp 2.25 inches from the $\frac{1}{8}$-inch aperture, the output of the first tube was on the order of ten volts, so that it is evident that the second tube must be capable of giving linear response when operated at a bias somewhat greater than ten volts. Obviously, it is necessary to introduce the attenuator after the second tube to avoid overloading the grid of the second high



Circuit Constants

L_1, L_2, Small push-pull output transformers.
L_3, 10-henry choke.
L_4, 30-henry choke.

C_1, 0.025 mf 400 v.
C_2, C_3, 0.05 mf 400 v.
C_4, 10 mf 25 v.
C_6, C_7, C_9, C_{18}, 8 mf 450 v.
C_5, C_8, C_{13}, C_{16}, C_{23}, C_{25}, 1 mf 450 v.
C_{10}, C_{15}, C_{19}, C_{24}, 5 mf 25 v.
C_{11}, C_{20}, 0.02 mf 400 v.
C_{14}, C_{22}, 0.002 mf 400 v.
C_{17}, 2 mf 400 v.
C_{12}, C_{21}, 0.0035 mf mica.

R_1, R_{14}, 20,000 ohms.
R_2, R_{19}, R_{22}, 0.5 megohm.
R_3, 500 ohms.
R_4, 2.0 megohms.
R_5, 1500 ohms.
R_6, R_{25}, 0.1 megohm.
R_7, R_{29}, 1.0 megohm.
R_8, R_{21}, 0.25 megohm.
R_9, R_{27}, 50,000 ohms.
R_{11}, 800 ohms.
R_{12}, 2000 ohms.

R_{13}, 1000 ohms.
R_{15}, 90,000 ohms precision.
R_{16}, 9000 ohms precision.
R_{17}, 900 ohms precision.
R_{18}, 100 ohms precision.
R_{19}, 4000 ohms.
R_{24}, 3000 ohms.
R_{28}, 25,000 ohms.

M_1, 0–1.0 milliampere.
M_2, 0–200 microamperes.

FIG. 1. Circuit diagram of oscillator, power amplifier, and glow lamp assembly.

[1] L. A. Jones, *Photographic Sensitometry* (1931), pp. 61–63.

gain tube, and to couple the attenuator, the second tube must be suitable for working into a low impedance load. The 6K6G tube meets these requirements.

Since density is defined as the logarithm (to the base ten) of the reciprocal of the transmission, the attenuator fixed resistances are chosen so that each step on the switch corresponds to a ten times increase in voltage, or to a unit change in density. The attenuator potentiometer is made 20,000 ohms in order to realize a reasonably high voltage gain in this stage, and still use a wire-wound potentiometer. The rather large plate current of the 6K6G is by-passed through a 30-henry choke.

The circuit constants in the high gain stages correspond closely to the tube manufacturer's recommendations.

To indicate the output, a 6J5G tube is used in a vacuum tube voltmeter circuit, with a 200-microampere meter in the plate circuit.

Because of the high voltage gain, decoupling filters are used throughout.

A power supply with automatic voltage regulation must be used, to ensure constant voltage gain, and constant light output from the glow lamp.

III. Mechanical Design

The glow lamp and tubes are mounted on top of a steel chassis, and the photo-cell and all inductances, resistances and condensers below. A $\frac{1}{8}$-inch aperture in the chassis above the photo-cell admits light from the glow lamp, which is directly above. Since the circuit does not amplify the effect of steady light and discriminates against the lower frequencies, daylight and light from tungsten lamps entering the cell housing through the aperture has no effect on the operation of the device. However, since a photographic deposit scatters[2] an appreciable amount of the light incident upon it, it is necessary to mount the cell very close to the aperture in order to approximate a measurement of "diffuse density." If only the light transmitted by the emulsion with small deviation from its original path is measured, the resultant quantity is defined as "specular density," and it is necessary to collect and measure all the transmitted light in order to obtain the "diffuse density." Since the conventional cell cannot collect all the light passing through the aperture even when the glass envelope is in contact with the chassis below the aperture, it is necessary to apply a small correction factor, as will be shown below.

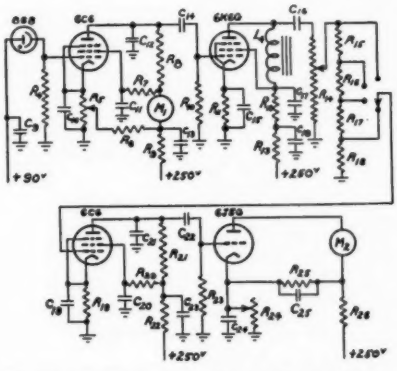


Fig. 2. Circuit diagram of photo-cell amplifier, attenuator and vacuum tube voltmeter assembly. See Fig. 1 for circuit constants.

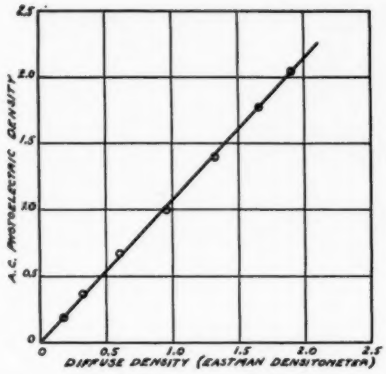


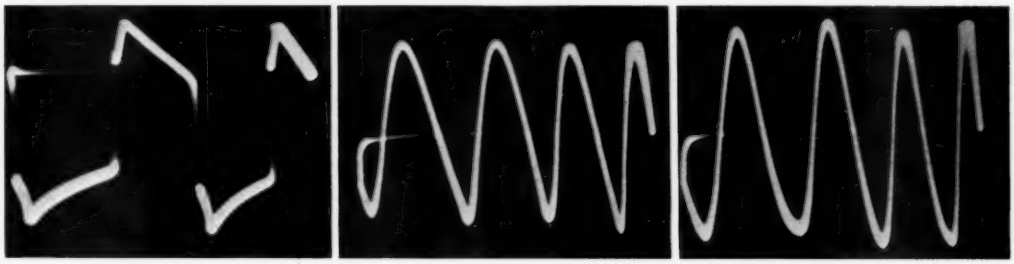
Fig. 3. Comparison of readings of Eastman and a.c. photo-electric densitometers.

The first stage is completely shielded below the chassis, and the arrangement of component parts of the circuit is such as to minimize reaction between stages.

IV. Calibration and Operation

A convenient method of calibration is by means of a beat frequency oscillator and a pair of decade resistance boxes, using the frequency at which the amplifier is to be operated, and

[2] L. A. Jones, *Photographic Sensitometry* (1931), pp. 55–60.



A B C

FIG. 4. Oscillograms showing suppression of harmonics in amplifier.

applying the signal to the grid of the attenuator tube. Adjust the bias of the voltmeter tube to 70 microamperes with no signal, set the decade boxes to give 0.1 maximum signal, and adjust the output of the oscillator to give a reading of 100 microamperes with the attenuator potentiometer at the top of its scale, advancing the unit switch one step, if necessary. Adjust the decade boxes to increase the signal by tenths to maximum signal, keeping the output of the oscillator constant, and for each value of the signal, determine the setting of the attenuator necessary to keep the plate current of the voltmeter tube at 100 microamperes. Plot the log of the reciprocal of the signal fraction against degrees rotation of the potentiometer, using semi-log paper, if desired, to open up the low density end of the scale. The scale readings corresponding to values of 0.1, 0.2, etc., of the log reciprocal signal are the desired fractional density scale divisions. An alternate method is to plot degrees rotation against the reciprocal of the signal on log log paper, and superpose a ten-division linear scale upon the reciprocal signal scale to determine the density scale divisions.

In operation, after a short warm-up period, the bias on the voltmeter tube is adjusted to give 100 microamperes plate current with the aperture clear, and the density scale set to 0. Place the sample to be measured over the aperture, and adjust the attenuator to again give 100 microamperes plate current. Read units of density from the switch scale, and decimals from the attenuator scale. Be sure to reset the attenuator for 0 density before removing the sample, to avoid damage to the microammeter.

V. EXPERIMENTAL RESULTS

A number of strips of exposed film were made up, covering a range of densities up to about two. These were measured on an Eastman visual comparison densitometer, and upon the densitometer described above. The results are shown graphically in Fig. 3.

In the Eastman densitometer, the incident light is diffused by a slab of opal glass, so that it reads diffuse densities. The slope of the line in Fig. 2 is 1.08, so that the photoelectric densities must be divided by this factor if it is necessary to convert them into diffuse densities.

Figure 4 shows how the shunting condensers remove a large part of the harmonic content of the input wave. Oscillograms *A*, *B* and *C*, respectively, show the wave form at the input to the glow lamp, at the output of the first amplifier stage, and at the input to the vacuum tube voltmeter.

After a warm-up period of about five minutes, the densitometer described above will operate for long periods with good stability and negligible drift. It may be used in brightly lighted rooms, either in daylight, or under 60-cycle tungsten lamps. It is rapid in operation, over 600 readings having been obtained in a four-hour period. Results are accurately reproducible. It is rugged, and is constructed of inexpensive standard parts.

ACKNOWLEDGMENT

The author gratefully acknowledges the interest and the many helpful suggestions of Dr. C. B. Bazzoni, under whose direction the development of this densitometer was carried out.

A Simple Photox Photometer Head

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(Received October 14, 1938)

A null-reading photometer head is described which employs a Photox cell integrally mounted with a graphite-graphite commutator in such manner that the direct current in an external instrument is reversed synchronously with the exposure of the cell to standard and unknown source. The candlepower of a Mazda lamp may be read directly on a permanent scale.

PHOTOELECTRIC elements have been used for photometric purposes since their earliest invention. It was soon recognized that absolute measurements could be made of light intensities only with great precautions of calibration.[1] A typical example of a photoelectric photometer operated under conditions of frequent calibration has been described by Weaver.[2] To avoid the annoyance of vagaries in light-sensitive elements and accompanying amplifier circuits, early attempts were made to use a single element exposed alternately to a standard source and to the unknown. It appears that Behr[3] was one of the first to emphasize the possibilities inherent in a system of this type. Employing a sluggish galvanometer with a period of twenty seconds, he exposed the element in succession to two beams of light under comparison, simultaneously reversing the galvanometer connections. To obviate too strong a torque on the coil, an auxiliary battery was included to send opposite and approximately equal currents through the galvanometer. The complete measurement cycle occupied nearly two seconds. It would be correct to assume that if the instrument showed no resultant deflection the two beams were of equal intensity.

In 1926, Sharp and Kinsley[4] undertook to investigate the feasibility of using photoelectric methods for checking quality of incandescent lamps in production. After postulating certain essential specifications as to desired performance, they proposed and developed a null device in which a potassium phototube was actuated alternately by a standard and unknown source through the mechanism of a rotating mirror. The output of the phototube was amplified and fed into the primary of a transformer, the secondary of which was connected to a galvanometer through a sliding commutator integral with the mirror shaft. Difficulties were encountered with the commutator and amplifier. A couple of years later, Sharp and Smith[5] described an "improved" circuit in which the sliding contacts were replaced by butt contacts on an oscillating arm operated by a cam and the amplification was spread out over three stages, instead of one, to gain stability.

A clever method of eliminating a mechanical commutator was proposed by Young.[6] His phototube was actuated alternately by means of a rotating shutter, the pulsating current was amplified and sent through the movable coil of a special instrument in which the field was established by a fixed coil energized by the same a.c. supply which operated the synchronous shutter motor. Thus the instrument torque was reversed for each source of light and null adjustment was readily obtained.

With the advent of the photo-cell (photovoltaic element) it seemed that a more suitable tool was available for photometry. Lange[7] suggested a double-faced cell to act as a differential indicator (with galvanometer) for two beams of light on a photometer bench. Gleason[8] studied a similar system employing two commercial selenium cells in opposition. Although good measure-

[1] Gibson in *Photoelectric Cells and Their Application*, by John S. Anderson (Physical and Optical Societies, London, 1930), p. 157; Harrison, *ibid.*, p. 118; Ives and Kingsbury, J. Opt. Soc. Am. **21**, 541 (1931).
[2] Weaver, Trans. III. Eng. Soc. **23**, 441 (1928).
[3] Behr, J. Opt. Soc. Am. and Rev. Sci. Inst. **10**, 288 (1935).
[4] Sharp and Kinsley, Trans. III. Eng. Soc. **21**, 117 (1926).
[5] Sharp and Smith, Trans. III. Eng. Soc. **23**, 428 (1928).
[6] Young, U. S. Patent 1,672,672.
[7] Lange, Physik. Zeits. **31**, 964 (1930).
[8] Gleason, Rev. Sci. Inst. **3**, 556 (1932).

ments could be made, it was observed that accuracy was limited by unequal variations in cell characteristics.

A rather obvious modification of Lange's and Gleason's technique is to use a single cell with commutator, but to choose a cummutator free from the defects encountered by previous investigators in using photoemissive elements. The writer has built for laboratory purposes an extremely simple photometer head which comprises a commutator having graphite brushes on graphite segments. Baker[9] has published measurements on the voltage drop between sliding graphite-graphite contacts which show that the contact resistance is low, uniform and linear with current. Hence it should be possible to reverse small currents reliably without disturbing irregularities.

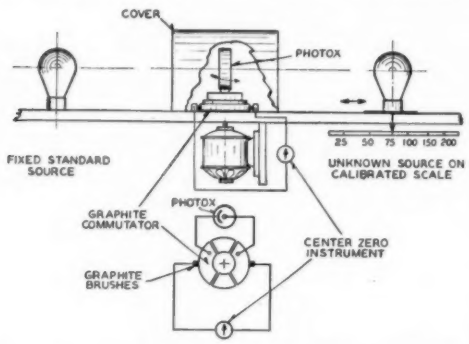

FIG. 1. Schematic sketch and wiring diagram of null indicating, direct-reading Photox photometer.

Figure 1 illustrates schematically the experimental arrangement actually followed in assembling a working model of a null photometer head, the calibration of which is independent of aging of the cell. The photoelectric unit is a copper-oxide disk (Photox) mounted in a micarta case. Although the Photox is known to depreciate at an average rate of about one percent per month, its color response is quite similar to that of the eye, and retains a high level of power output over long periods of time (the order of 0.5 microwatt per foot-candle).[10] The Photox is attached to an industrial socket which in turn is attached to a horizontal commutator. As shown, the commutator consists of a pair of 120-degree segments and a pair of 60-degree segments, all insulated. The Photox is connected permanently to the two large segments. This integral assembly is rotated at about 1750 r.p.m. by a small induction motor. When the cell faces the standard lamp, the graphite brushes contact the centers of the live segments. When the cell faces the unknown lamp, the current in the brush circuit is identically reversed. The indicator is simply a sensitive, zero-center microammeter. It may conveniently be one of the inexpensive miniature panel instruments with cobalt steel magnets which are now available commercially. As suggested in the sketch, the unknown lamp may be mounted in a movable carriage with fiducial mark; and, for example, a scale may be calibrated directly in units of candlepower. Needless to say, the cell must be shielded from any extraneous illumination.

For comparisons at low levels of intensity, it would be necessary to substitute a more sensitive instrument, such as a wall-type galvanometer or an equivalent vacuum tube amplifier.

[9] Baker, Elec. J. **31**, 359 (1934).

[10] Wilson, Elec. J. **32**, 270 (1935).

A Simple Method for the Determination of Extinction Coefficients Using the Hydrogen Lamp as Light Source

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(Received November 2, 1938)

IN THE measurement of the absorption spectra of solutions by photographic methods it has been customary to use a spark as light source and to determine the extinction coefficients by matching of the spectra taken through the solution with definitely controlled comparison spectra. The difficulty in detecting weak or narrow absorption bands under these conditions is well known. The use of a continuous light source such as the hydrogen lamp and the avoidance of a number of comparative spectra which make the presence of very weak bands much more difficult to detect offers distinct advantages if the method can be made sufficiently accurate to determine extinction coefficients within the limits obtainable by the other methods.

A simple method which involves taking only one comparison spectrum on a plate has been found to give very satisfactory agreement with results obtained by the Henri method in use in this laboratory.[1] When a continuous light source is used, the point on the photographic plate at which absorption is sufficiently strong that the blackening of the plate just disappears can be readily and quite accurately determined by visual examination. The determination of the limits of absorption by the disappearance of blackening on the photographic plate was the basis of the early Hartley-Baly method where a spark was used as light source. The great variation in intensity of the lines in the spark spectrum gave wide latitude in the selection of the point at which absorption began and made the recognition of the limits of absorption difficult and inaccurate; the sensitivity of the photographic plate as a function of the emulsion used, the time of exposure and the method of development was not taken into consideration so that such measurements did not admit of any quantitative determination of extinction coefficients. The use of a hydrogen lamp, the intensity of which under controlled conditions is constant throughout the spectral region under consideration, and the determination on each plate of a standard extinction coefficient are modifications of the older method which have made possible a very simple quantitative measurement of extinction coefficients.

The molecular extinction coefficient is defined by the expression

$$E = 1/cd \log I_0/I,$$

where c is the molar concentration, d is the length of the absorbing layer in cm, and I_0 the intensity of the incident and I that of the transmitted light. If the value of $\log I_0/I$ is known for the points on the photographic plate at which the transmitted light is decreased to such an extent that it no longer blackens the photographic plate and if this $\log I_0/I$ should be constant for a given light source and for all wave-lengths on the plate, then E can be readily evaluated since c and d are known.

To test experimentally the constancy of k in the expression $k = \log I_0/I$ for the points on the photographic plate at which the blackening just disappears, a large number of plates were examined on which extinction coefficients had been determined by the usual Henri method and the value of $Ecd = k$ was calculated. Using the hydrogen lamp as light source, the absorption spectra of the same substances were photographed and the limits of absorption, as measured by the disappearance of blackening, were determined. When these wave-lengths were plotted against the value k, calculated from $Ecd = k$, the graph showed that the value of k, while dependent on the type of plate used, its development and the time of exposure, is independent of the spectral region within fairly large limits. For Eastman No. 40 plates these limits extend from the visible to 2400A and for the special ultraviolet sensitive plates to somewhat shorter wave-lengths.

A photoelectric densitometer curve, in which the galvanometer reading is plotted against the

[1] F. Twyman and C. B. Allsopp, *The Practise of Spectrophotometry with Hilger Instruments* (London, 1934), second edition, p. 23.

wave-length, is shown for a No. 40 plate in Fig. 1. Since the galvanometer was read directly rather than recorded photographically, the mercury reference lines which appear in our hydrogen spectrum have been omitted.[2]

It seems probable that this quite surprising result is caused by the cancellation of two opposing effects. On the one hand, the sensitivity of the photographic plate decreases toward shorter wave-lengths[3] and the dispersion of the

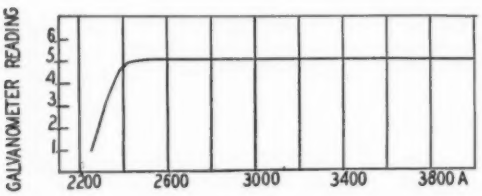

FIG. 1. Photometric curve showing the continuous hydrogen spectrum on an Eastman plate No. 40.

spectrograph increases so that both factors tend to lessen the blackening of the plate with shorter wave-lengths. On the other hand, the intensity of the continuous hydrogen spectrum increases from the visible to about 2500A; from this maximum it decreases slowly to the end at 1650A.[4] This constancy of blackening of the plate between 4400 and 2500A was observed by Finkelnburg.[4] Under the conditions of our experiment the decrease in blackening between 2500 and 2400A is so slight, as shown in Fig. 1, that it can be neglected. For wave-lengths shorter than 2400A the blackening shows a sharp decrease, as would be expected.

Since the experimental results show that the value of k is constant over the spectral region under consideration this quantity needs to be determined only once for each plate, provided the exposure time is kept the same throughout. In our experiments an exposure time of from 30 to 45 seconds with the hydrogen lamp operated on a current between 300 and 400 milliamperes gave the most satisfactory conditions.

In practice the value of k for each plate was determined by placing a standard filter, whose extinction coefficient, k', had been measured independently for a series of wave-lengths, between the slit of the spectrograph and the Baly tube containing the pure solvent and taking an exposure for exactly the same time as would be used for the solution spectra. The length, d, of the solvent tube was usually three cm, since with spectrographically pure solvents the difference in transmission between the limiting lengths used in the Baly tube, 0.3–7 cm, was found to be negligible. The value k' for the wave-length at which the blackening just disappears on the spectrum taken through the filter would be therefore the value of k for the whole plate.

The filter which was used in our experiments was a very thin glass plate whose extinction coefficients over a given range of wave-lengths had been measured by the Henri method and recorded in the form of a graph. While the constancy in operation of a hydrogen discharge over a long period of time is well known, there is a

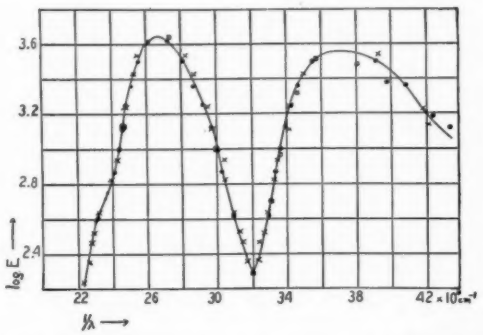

FIG. 2. Absorption curve of potassium chromate in water solution taken by the Henri method (x), by photoelectric measurement[5] (□), and by the method described in this paper (●).

disadvantage in its use in that it is not a point light source and cannot therefore be focused on the slit. With a spark light source the rays pass through the Baly tube without hitting the walls, but with the hydrogen lamp there is some reflection from the walls and the amount of this reflected light was found to vary with the position of the inner tube. This difficulty was readily overcome by placing a coating of black paper on the walls of the inner tube.

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[2] The photometric measurement was made in the laboratory of Physical Chemistry at Harvard University by Dr. Lucy W. Pickett to whom I wish to express my grateful appreciation.

[3] F. Weigert, *Optische Methode der Chemie* (Leipzig, 1927), p. 213.

[4] W. Finkelnburg, Physik. Zeits. **34**, 529 (1933); Zeits. f. Physik **68**, 583 (1931).

The procedure adopted for the determination of an absorption curve is as follows: On each plate the hydrogen spectrum is first photographed without the filter in order that the purity of the hydrogen spectrum can be checked; then a spectrum through the filter and the Baly tube containing the solvent in order to determine k for the plate, and finally a series of exposures, are taken through different lengths of solution and through different concentrations as in the Henri method. The lengths used are varied by a constant ratio (3 : 4 or 4 : 5).

Figure 2 shows the absorption curve of potassium chromate in water solution as measured by the Henri method (x) and by the method which has just been described (•), the logarithm of the extinction coefficient being plotted against the wave number. The standard values, as given by Roessler,[5] determined by photoelectric measurements have also been included to show the accuracy of the two photographic methods.

If a type of photographic plate were used in which the value of k happened not to be constant over so long a spectral range this method might still be applicable if another kind of filter were used. A quartz cell adjusted to the proper length and containing potassium chromate solution of the necessary concentration could be used as a standard filter. It would then be possible, as is shown in Fig. 2, to obtain with one exposure four values of k for four different wave-lengths.

[5] S. Roessler, Ber. d. Dtsch. Chem. Ges. **59**, 2608 (1926).

Book Review

Color and Colors. MATTHEW LUCKIESH. Pp. 205, 15×23 cm. D. Van Nostrand Company, Inc., New York, 1938. Price, cloth, $3.00.

Color and Colors is addressed to the general reading public. The purpose of the book is to encourage more widespread use of color by reviewing the powers of colors to stimulate emotions, and by dispelling the fear that brilliant colors are inherently gaudy and undesirable. A rather complete review of the various meanings associated with colors in various nations and ages demonstrates primarily that such meanings arise from cultural and historical associations and that the use of colors need not be seriously restricted by fears of unintended symbolisms. The wider use of rich colors is encouraged by a review of the basic principles of color harmony. According to the author, these rules are easily mastered and are aids rather than restrictions on imaginative use of color. One principle to which reference is repeatedly made is expressed in the words of the author: "Man is still Nature's child. . . . He may produce novel effects, but effects to live with must possess some elements of the natural." The chapter on "Mobility of Light" is apparently closest to the author's interests and contains some of the most interesting and least repetitious passages in the book. The use of continuously variable distributions of colored illuminations throughout a room or other space is described enthusiastically, and the efficacy of such use of light in controlling emotions is said to be comparable with the effects of music. The possibility of establishing any parallelism between music and color is considered remote, even if conceivable. The gradual elaboration of an aesthetics of mobile color through usage and association may develop an art comparable with the musical art which has gradually developed through centuries of experimentation. There is no reason to believe that an art can be invented by the discovery of a method of translating music into mobile color.

Much emphasis is placed on an analogy between an ensemble of color and a dramatic play, and between the separate colors and the players. The potentiality of each color to play either a dominating or an accessory role, and to excite, subdue, or depress the tone of the ensemble is described as analogous to the ability of each player to play various roles and represent various characters. It may be questioned whether the contributions to clarity and subject matter gained by the introduction of this analogy justify the elaboration with which it is developed and repeatedly reviewed. Many of the readers to whom the book is addressed may not agree with the repeated assertion that the present age is less enterprising than past ages in its use of color, and that this timidity results from "mental color blindness" which the author describes as a disease afflicting most of civilized mankind. Many might agree that the increase in use of color has not kept pace with the rate of development of new colorants, but they would attribute this lag more to the conservatism of manufacturers than to lack of demand from consumers. Finally, physicists may well challenge the assertion that there seems to be no hope for the general adoption of instrumental methods of measurement, specification, and control of colors "because they are not practicable enough" (page 91). The most successful contemporary advances toward the standardization of colors which the author urges as desirable are resulting from the use of spectrophotometry and standardized colorimetry.

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